INDOT Research

TECHNICAL *Summary*

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Implementation of Steel Bridge Protection Policy

Introduction

To prevent deterioration of a bridge condition leading to structural deficiency through corrosive actions, choosing and applying a suitable coating system on the steel bridge surfaces are very important. Moreover, it can further protect the painted bridges to use explicit contract wording to warrant the quality of bridge painting work after the substantial completion of the painting project. This study is intended to further develop warranty clauses and computerized image processing system previously used on an INDOT steel bridge painting demonstration project.

The study found eleven elements essential for the successful warranty contract application. They are: warranty period, defects definition, inspection schedule, repair procedure and progress schedule for correction work, season of work, liability insurance, traffic control, supplementary performance bond, supplementary lien bond, surety company, and work permit.

Conventional visual inspection method does not provide accurate data for the steel bridge painting quality assessment. Various disputes may arise between INDOT inspectors and bridge-coating contractors over the reliability and objectivity of the inspection. Thus, digital image processing methods are developed to provide a more reliable and objective approach for painting quality assessment. In this report, various digital image processing methods are studied and they are compared with each other in terms of different environmental situations.

Findings

Researchers performed an extensive study through literature review and collected warranty clauses from other states that established and applied bridge painting warranty clauses. In the study, eleven elements were found in forming a successful warranty contract for the INDOT steel bridge painting projects. The eleven elements are:

- Warranty period
- Defects definition,
- Inspection schedule
- Repair procedure and progress schedule for correction work
- Season of work
- Liability insurance
- Traffic control
- Supplementary performance bond
- Supplementary lien bond
- Surety company
- Work permit

Furthermore, a 5-year warranty period, 50% bond value requirement and the developed digital image recognition method for objective rust identification are found as the most comparatively appropriate measures to better assure INDOT steel bridge painting quality when the warranty clauses are put into a large-scale implementation.

For objective and consistent defect recognition, NFRA (Neuro-Fuzzy Recognition Approach) system was developed in this study. NFRA utilizes image processing, fuzzy set and neural networks as tools for visual image capture, recognition, analyses, and defect determination. Therefore, it provides a more reliable and unbiased approach for paint condition assessment.

Fuzzy set theory and neural networks are incorporated into the developed system to simulate the inspector's eyeball judgment and automate the process for determining the rust percentages on the steel bridge. Moreover, they provide better handling of low-quality images through their fault-tolerant characteristics. To facilitate the practical application of NFRA, three other methods were further studied. They are: ISKA (Illumination-based Segmentation and K-means Algorithm), KMNS (K-means Algorithm), and SKMN (Simplified K-means Algorithm). The study found that SKMN method demonstrated comparatively better performance than the others under different conditions in terms of brightness, angle, distance, and cleanness. SKMN method divides the object area and background area from the captured image and uses the K-means algorithm for defect recognition. Thus, SKMN method is recommended for future large-scale implementations.

Implementation

(1) After consulting with many INDOT bridge inspectors, bridge painting contractors and surety companies regarding the use of the proposed warranty clauses, it is recommended that the proposed painting warranty clauses be implemented in a large-scale basis to INDOT steel bridge painting contracts.

(2) To fully make use of the advantages of warranty contracts, a follow-up study should be preceded in the future to continuously evaluate the large-scale implementation. The most contentious issues in warranty practice are to determine warranty period and warranty value. The use of warranty period ranges from 2 years to full service life and warranty value varies from 20% to 100% of total contract amount among many DOTs. To optimize the balance between warranty period and warranty value will be the focus of this task. Optimal warranty period and value will minimize the unnecessary cost and use of warranty clauses will enhance the accountability of painting contractors in the long run.

(3) The developed SKMN method uses digital image processing techniques to enhance the objectivity and consistency of the steel bridge painting quality assessment. An associated random sampling plan is also suggested in this report for the large-scale implementation. Since taking paint images from an entire bridge is nearly impossible, the proposed sampling plan will complement the effective use of SKMN. The combination of a random sampling plan, an image acquisition, and an image processing method for rust percentage determination lays a solid foundation for the large-scale implementation of SKMN method in the future to assure INDOT steel bridge painting quality.

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FINAL REPORT

FHWA/IN/JTRP-2001/29

IMPLEMENTATION OF STEEL BRIDGE PROTECTION POLICY

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16. Abstract

Many Departments of Transportation (DOTs) have made tremendous efforts for managing their civil infrastructure systems effectively and to meet public demands for their performance and safety. The introduction of warranties help many DOTs keep their construction with better quality by shifting post-construction responsibilities to contractors. Warranties are applied to numerous items according to each DOT’s needs, and this research focuses on steel bridge painting protection policy for Indiana Department of Transportation (INDOT).

This research represents the development of an implementable warranty clause for protecting steel bridge painting and the image processing technique for the objective and quantitative painting quality assessment. In the warranty clause development, extensive literature review was performed and many currently used steel bridge painting warranties were analyzed and compared. It was found that eleven items consist of the core issues for successful bridge painting warranty projects. The eleven elements are warranty period, defects definition, inspection schedule, repair procedure and progress schedule for correction work, season of work, liability insurance, traffic control, supplementary performance bond, supplementary lien bond, surety company, and work permit. These elements are used to framework INDOT’s warranty clause for protecting its steel bridge painting.

In addition, this report proposes the various image processing techniques that can recognize the rust on the steel bridge surfaces. The computerized techniques are constructed for unbiased rust recognition and percentage determination in terms of distance, angles, brightness, and cleanness. The report explains the theoretical background and the application procedures and examples. Random sampling plan and stepwise applications are also proposed.

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CHAPTER I
INTRODUCTION

1.1 Research Objectives

To prevent the early failure of paint systems on steel bridge surfaces and to ensure public safety in Indiana, a JTRP research project entitled “Steel Bridge Protection Policy” was completed three years ago. This research is a follow-up implementation research project. It is intended to further develop and monitor the experiments.

In the previous research, INDOT experimented with steel bridge painting warranty clauses in a demonstration project. Meanwhile, to facilitate the objectivity and accuracy of determining the percentage of rust on the painted steel bridge surface in the demonstration project, the warranty clauses were used with the assistance of a computerized image processing system developed in another INDOT research project entitled “Optical Imaging Method for Bridge Painting Maintenance and Inspection.” After the research proposal was approved and thorough discussion among the Study Advisory Committee (SAC) members, there was a consensus that further refinement of the used warranty clauses and computerized image processing system is necessary to facilitate INDOT inspectors’ decision making on accepting or rejecting the painting work performed by painting contractors. Therefore, the SAC directed that the objectives of this research should focus on:

1. The enhancement the efficiency of the proposed warranty clauses implemented on INDOT demonstration projects;
2. The facilitated use of computerized image processing by monitoring related parameters and developing strategic sampling plans.

1.2 Research Methodology

The research was divided into eleven tasks as follows:

1. Literature Search

The purpose of the literature review was to find any information from latest studies on the topics of warranty clauses and image processing. This procedure also helped in structuring the research. Once a beginning process is determined for a research project, knowledge and qualitative information can be combined to produce effective results in the research. Subsequently, a search on the topics in the published books and technical journals was performed.

2. Background Review on Warranty Clauses

A broad review of in-service warranty clauses currently used by INDOT was conducted, and those clauses already recognized as potential candidates for immediate use by other states were also evaluated. This step also included an investigation of the major problems encountered, any possible pitfalls, and the potential parameters attributing to successful performance.

3. Literature Search and Review on Digital Image Processing

An extensive investigation on the topics of digital image processing used in other states, industries, and research institutes was performed. Moreover, another step was to develop digital image processing methods for this research and their applications in construction.

4. Equipment Purchase

The research team identified and purchased the needed image processing equipment, including hardware and software.

5. Development of Neuro-Fuzzy Recognition Approach (NFRA)

Poor image quality is always a tough problem to digital image recognition. NFRA was developed and proposed in order to deal with the difficulties associated with digital image recognition, such as effects of shadows and over-illumination. In this step, a new image recognition approach that combines the artificial neural network and the fuzzy logic system was developed.

6. System Testing

The experimental testing of the purchased equipment and NFRA was performed to set up the system and to ensure methodology and equipment implementation on site.

7. Data Acquisition

INDOT steel bridges and rusty steel beams in Purdue campus were selected for data acquisition. Digital images were acquired from these bridges and steel beams for assessment. In addition, simulated ASTM templates were enlarged and experimented for testing the validity and reliability of the determination of rust percentages on the images captured.

8. Analysis

A thorough system analysis was made on data collected to achieve reliable results for step-by-step implementation. The main part of this stage was to obtain sample images for the initial system development and training using neural networks. The objective was to determine the presence of rust in coating and to provide quantitative measures of these rusts.

9. Comparison of Various Techniques

To further validate the validity and reliability of NFRA approach, more image processing techniques were developed and compared with the NFRA. The comparison was made based upon various experiments using numerous collected sample images.

10. Implementation and Sampling Plan

A pragmatic sampling plan for capturing images, step-by-step implementation procedures to determine the rust percentages, and warranty clauses for protecting INDOT steel bridge painting were developed.

11. Final Report

A draft final technical report was prepared and will be submitted to INDOT for final report. The report includes methodology used, references sited, experiments done and their corresponding findings, sampling plan, step-by-step procedures to determine the rust percentages, proposed warranty clauses and other related implementation plans.

CHAPTER II
PAINTING DETERIORATION AND WARRANTY

If a quick comparison was conducted between two or more warranty clauses in different areas of practice, it can be easily noticed that they generally handle the same issues. Although each of these clauses may have a completely different wording, the structural elements are very close to each other. What actually determines the strength or weakness of a warranty clause is the compliance and full sufficiency of its basic structural elements. Realizing this fact, a thorough literature review took place to build the abstract model that can be adapted for the steel bridges painting practices (Chang and Georgy, 1999).

2.1 Steel Bridges Painting Deterioration

While building the basic model of a warranty clause, it can be easily realized that the different elements composing this model have different degrees of importance. Although some of those elements incorporate into the development of the model, others can determine its success or failure. The most obvious example is the definition of defects that may arise from the poor performance of the contractor. The inability to clearly define both the various painting defects and the extent to which the contractor will be held responsible for them may result in excessive future disputes.

The Environmental and Workmanship Effects

Starting from the first day the painting system is applied on the bridge, it is subjected to continuous attacks from the environment. The severity of the environment determines to a great deal the expected life of such painting system. The SSPC (Steel Structures Painting Council) environment-zone approach is helpful in the semi-quantification of the type of environment (Hare, 1990.) However, within these general classifications, there are inevitably degrees of exposure not only from one part of the country to another but from bridge to bridge and even from section to section of a particular bridge, depending upon location, type of crossing, bridge design, and traffic volume. The three major classifications are:

- 1B-Dry Exterior.
- 2A-Fresh Water Wet.
- 2B-Salt Water Wet.

Most snow-belt structures undoubtedly should be classified as 2B, and that classification should worsen in the expansion bay areas or where deck leaks occur. Sheltered underdeck areas of bridges in good condition over non-water crossings might easily be classified as a rather mild 1B environment. Over inland waterways, a 2A rating might be more appropriate for the same underdeck steel and over a busy well-salted highway, splash back from the highway below will intensify the immediate environment beneath the bridge to class 2B (especially on the bottom flanges).

The environment is only one face of the coin. Poor surface preparation and inadequate film thickness have been widely held as being the predominant causes of the premature failure of the coating system (Hare, 1990). The poor workmanship from the side of the contractor which results in those occurrences can substantially reduce the service life of the painting system. An NACE (National Association of Corrosion Engineers) report estimates that some 70% of premature coating system failures may result solely from poor surface preparation.

While there is probably some truth in this, such generalities are dangerous because they foster a preconceived bias against the contractor. Unfortunately, it is not rare that coating failures are found to be outcomes of several apparently unrelated phenomena. This requires being more cautious in handling this issue. For any bridge, there must be a realistic evaluation of the environmental conditions surrounding it, and therefore better judgment about the life expectancy of the coating system. When there is a fast deterioration of the coating system beyond the expected rate, the failure can be claimed to be a result of the poor workmanship of the contractor.

Painting Failure Types and Causes

Steel bridges' painting is the principal protection strategy of the steel substrate against deterioration. With all of the variables involved in the formation and use of paints, there exists a wide variety of painting failure types. The types of these different failures can be classified into seven categories (SSPC, 1989.) The list includes : (1) failures due to the selection of the coating system, (2) failures which are inherent within the coating itself, (3) adhesion-related failures, (4) application related failures, (5) failures due to the substrate, (6) design-related failures, and (7) failure by exterior forces. Table 2.1 enumerates the different failure types that fall within each of the aforementioned categories. A group of failure types that are most frequent are described below (SSPC, 1989) and (Tam and Stiemer, 1996.)

Chalking

With chalking, the organic binder in the coating tends gradually to disintegrate on the surface releasing the pigments and allowing them to remain on the surface as powder or chalk. This is strictly a surface phenomenon. While in some cases it can result in rapid reduction in coating thickness, it is generally a relatively slow process and one which does not result in catastrophic failure or severe corrosion to the substrate.

Checking

Checking is an age-related failure of a coating. It is characterized by uneven and generally non-linear, non-continuous breaks in the coating. These breaks are primarily a surface phenomenon and do not penetrate the full depth of the coating. Checking can be characterized as “visible” if the checks can be seen with the naked eye, or “microscopic” if they can be seen only under low magnification. It is basically a formulation problem that results in surface stresses in the coating layer which causes the small checks to appear.

Cracking

Cracking is also an age-related failure. It contrasts with checking in that it is not a surface phenomenon but one where breaks in the coating penetrate to the underlying surface. This makes it a more damaging type of failure than checking, since corrosion can rapidly take place at the breaks in the coating.

Table 2.1. The various types of paintings failures (SSPC, 1989)

	Failures Due to Selection of the Coating System	Failures Inherent Within the Coating Itself		Adhesion-Related Failures
		Organic	Inorganic	
TYPES of FAILURES	Contingent upon the characteristical resistance of the coating system to the surrounding environment.	Chalking Erosion Checking Cracking Alligatoring Mud-Cracking Wrinckling Micro-Organizm Discoloration	Checking Mud-Cracking Chemical Reactions Pinpoint Rusting Pitting in Seawater	Blistering Peeling Flaking or Scaling Intercoat Delamination Undercutting

Table 2.1. The various types of paintings failures (Continued)

	Application-Related Failures	Failures Due to the Substrate	Design-Related Failure	Failure by Exterior Forces
TYPES of FAILURES	Improper Mixing Improper Thining Improper Thickness Oversray Pinholes Spatter Coat Holidays Cratering Bleeding Blushing Lifting Orange Peel Runs & Sags	Contingent upon the substrate material type and quality	Can arise from the difficulty of appltying paint due to complicated design of: Edges Interior Corners Discontinuous areas Welds Skip Welding Back to Back Angles	Chemical Erosion and Abrasion Faying Surfaces

Discoloration

Because appearance may be as much a function of a coating as its corrosion resistance, coatings that change color after application and become unsightly can be considered to have failed.

Pinpoint Rusting

Pinpoint rusting occurs primarily in areas that are thinner than the remainder of the coating, starting with an isolated pinpoint of rust showing here and there in these thin points. As time goes by, the pinpoints become closer together, and finally, at the time of full failure, the spots of pinpoint rust cover the entire surface.

Blistering

Blistering is one of the most common forms of adhesion related coating failure, particularly when the coating is immersed in water or sea-water. It can also occur in areas of high humidity where there is continuing or intermittent condensation on the surface. Poor application of the coating results in gases and liquids to develop within or under the coating that exert pressure stronger than both the adhesion and the internal cohesion of the coating. This allows the coating to stretch and to form the hemispherical blister. If the pressure is greater than the tensile strength, the blister will break. Afterwards, the substrate will be readily attacked, causing rust.

Peeling

Peeling is a coating failure usually caused by a coating having a tensile strength greater than its bond strength to the surface. Any coating will peel or pull from the surface if it has less adhesion to the substrate than it has tensile strength, or if it reacts adversely with the substrate over a period of time, thus substantially reducing the adhesion.

Flaking and scaling

These two types of failure are adhesion-related. Flaking is a term describing a condition where small pieces of coating detach themselves from the surface of the substrate. Its edges are generally raised up from the surface and the small pieces can rather be easily removed, leaving the bare substrate. Scaling is similar to flaking, except that the pieces that break away from the surface are much larger. Pieces of coating several inches in diameter may break due to aging stresses, curl and come off in large flakes. The two phenomena arise primarily from the poor surface preparation that reduces the required adhesion forces and leads to that problem.

Undercutting

Undercutting is another type of adhesion failure that involves the gradual penetration of corrosion underneath the coating from a break or pinhole in the film or from unprotected edges. It often occurs when a coating has been applied over mill scale. Moisture and oxygen penetrate the coating and react with the scale causing it to lose adhesion and thus form progressive corrosion beneath the coating. Most of these undercutting failures can be substantially reduced by proper surface preparation prior to the application of the coating and the use of a coating with strong adhesion characteristics.

Runs and Sags

Runs are downward movements of a paint film resulting when excess material continues to flow after the surrounding surface has set. Sags are also downward movements of a pint film but between the time of application and setting resulting in a curtain appearance. Both of the two problems may be caused by the use of too much wet paint. Coating failures usually occur because of a thin coating above the sag or run.

Responsibility of the Contractor

Whenever a certain form of failure appears on the bridge, the inspector encounters a problem of determining whether such failure is due to the environment attacks, the poor workmanship of the contractor, or both. The decision is not always easy to make. The reason is that it is not clear-cut between the two. However, some failures are more vulnerable to the poor workmanship than others. If a certain failure of such group appears within a short period of time after the substantial completion of works, it is more evident that the contractor is responsible for it while the environment attacks worsen the situation.

This sentence is true for those failures emerging for the improper surface preparation. For most cases, the improper preparation of the steel surface results in severe adhesion- and rusting-related problems. This includes blistering, peeling, flaking and scaling, and undercutting rust. Any remaining debris from the surface preparation process extensively accelerates the occurrence of those failures.

Another category of failure types associates with the application process itself. This category includes all failures that emerge from the improper paint mixing procedures, incompetence in applying the paint layers, and others. Some examples are the insufficient coating thickness, cracking, checking, discoloration, and above all the pinpoint rusting. Unfortunately, the environment affects the failure types just mentioned in this category in varying degrees which makes the judgment process more difficult. While the contractor is responsible for any over-thinned areas of the coating system, unless an abrasion from the environment is apparent on the surface, it is difficult to impose such responsibility on him in case of rusted areas in leaking areas or where dicing ice is used extensively. At the same time, the inspector should keep in mind that even with the severe environment, a coating system resulting from a good job can last for some reasonable period of time without apparent deficiencies.

2.2 The Basic Model of Warranties and Guarantees

Warranties and guarantees are contractual commitments extended by the contractor to the contract owner. As a practical matter, the terms are synonymous in the context of construction contracting. The most basic warranty extended by contractors is the warranty of workmanlike methods applied during the contract period. Most contracts include a statement that the contractor extends such a warranty. The wording varies, of course, but typically the contractor warrants that he will use construction methods and techniques that are recognized as acceptable within the trade or industry and that his work will sustain acceptable for a fairly long period of time after the end of the contractual works (Jervis and Levin, 1988.)

Express and Implied Warranties

Two types of warranties are recognized under the law; express warranties and implied warranties. The term implied warranties mean that the construction products must be capable of passing in trade under the contract description and are fit for the purposes intended. Express warranties are those that specifically set forth in the contract itself (Fisk, 1997). If a construction contract does not contain an express warranty, courts will be quick to read an implied warranty into the contract. However, when reading an implied warranty into a contract, courts are somewhat restrained in determining the scope of the warranty. An express warranty will be broader than the implied warranty a court will find. Therefore, express warranties are more useful for owners and may enable the owner to hold the contractor to higher standards and commitments (Jervis and Levin, 1988).

Scope of the Warranty

The final construction product is subjected to all kind of factors that affect its life time. Among those factors, the workmanship of the contractor during the construction activity plays the major role. Nevertheless, a variety of external factors may affect the performance of the final product. The list includes the different environmental conditions, the abuse from the owner side or the end users, and the deficiencies associated with the material used. Contractors rely on those external factors to reason for all the apparent defects after the end of the construction-related works. This can cause a hassle for the owner to prove that the contractor workmanship has led to the existing defects.

The disturbance usually arises from the vague and puzzled wording of the warranty clause. As a matter of practice, a clear definition of what is considered a defective work owing to the poor workmanship of the contractor and the presence of standardized measurement procedures of those defects saves the owner a lot of effort. To reach a clear and well-defined scope of the warranty, three items must be included: (1) a clear definition of the defects that the poor workmanship may incorporate in its occurrence, (2) the typical method of measurement of the degree of severity for all the predefined defects, and finally (3) the limit that identifies the contractor involvement in the occurrence of the defect.

Warranty Period

Express warranties generally run for a stated period of time called the "Warranty Period." This means that if during the warranty period, the owner notifies the contractor of a defect in his work, the contractor must return to the job site and correct the problem at no charge to the owner. If there is a dispute as to whether the item falls under the warranty, the owner has the burden of establishing that the problem does in fact result from defective workmanship by the contractor during the execution of the works (Jervis and Levin, 1988.)

A common question that arises regarding warranties is the expiration date. As the express warranty typically runs for a certain period of time defined in the warranty clause wording, the determinative factor is the date the warranty starts to run. This factor, however, differs in accordance with the scope of the contract works. For most cases, contracts state that the warranty runs from the date of substantial completion. This is the date when the project becomes suitable for its intended purpose and the owner is able take occupancy and make use of the structure. When the purpose of the contract works requires the execution of such works into stages, the date can be set relative to the completion date of each stage. Consequently, each stage will have its own expiration date.

Performance and Payment Bonds

The existence of a written commitment in the contract wording does not fully guarantee the execution of the required corrective works. This is primarily due to the changing environment of the construction industry which may cause the contractor to become financially unable to do the job or continue what he has already started. Such possible risks highlight the need for warrant bonds. A warranty bond introduces a third party, i.e., a surety company, that guarantees the payment of a satisfactorily compensating amount of money in case of the contractor's failure to do the job. Bonds are regarded as a relatively quick and easy way to protect the various interests of the owner, contractor, and suppliers of labor and materials.

Two basic kinds of bonds are utilized after the establishment of a contractual agreement: performance and payment bonds (Stokes and Finuf, 1992.) Although this is not mandatory in private works, it is usually required in all public works (Fisk, 1997.) Those bonds are typically required by the owner after the award of the contract. A new set of bonds must be submitted by the contractor before the end of the contract works to guarantee the execution of repair works that may take place during the warranty period.

Under the terms of a performance bond, the surety company guarantees that the contractor will complete the required works to the satisfaction of the engineer and pay for any costs due to the contractor's failure to comply with its contract requirement. The benefit of the performance bond even exceeds that. Sureties usually review the financial position of the contractor as well as other qualifications before the issuance of the performance bond. This study helps in preventing the stoppage of works owing to the sudden insolvency of the contractor.

A payment bond is an additional remedy for suppliers of labor and materials in the event the contractor fails to pay whatever they have furnished for the project. The surety has an obligation for the owner to pay for the additional costs arising from such failure by the contractor.

Fisk (1997) mentioned that the customary amount of public works bonds is 100 percent on performance bonds and 50 percent on payment bonds. It is crucial that the reader realizes the previous figures are for the original contract works for which the first set of bonds will be typically issued. The Construction Industry Affairs Committee of Chicago, with membership spanning both the design profession and the contractor associations recommends that both the performance and payment bonds be written in the amount of 100 percent of the contract price.

It is rational that the original set of bonds to be around the contract price or more. Basically, the bond is supposed to guarantee the works as specified in the contract drawings and specifications. However, the issue is different in case of the warranty bonds since the expected defects cannot be in the amount of the contract price. The value of the new set of bonds issued by the end of the contract is usually determined according to the owner's discretion. The basic drawback associated with the issuance of the performance and payment bonds is the increase in the incurred costs. Overstating the amount of the two bonds will increase the costs beyond the justified amount for the project works. Although the performance and payment bonds give the owner a satisfactory guarantee for the completion of the repair works during the warranty period, he may encounter a situation of no defects encountered while the contract price was increased by the contractor to cover the bonds fee. The owner has to trade-off between the value of the payment and performance bonds and that of the expected increase in the contract price according to the expected performance by the contractor.

Special Permits

For the special practice of public works, the owner (typically a public authority) may have its own regulations and rules that govern the flow of works in its contracts. Each owner has to tailor the warranty according to the special needs and requirements he may desire. Complete attention must be taken not to add any wording that may seem unreasonable to the contractor and result in a noticeable augmentation in the contract price.

CHAPTER III
SEARCH AND USAGE OF WARRANTY CLAUSES

Warranties are commonly used in most industries. People realized long ago that without a written warranty in a terminated contract, the other party has no further responsibility for the quality of works he has performed during the contract period unless an explicit breach of the common law exists. In the past few years, INDOT has experienced an increasing number of the deteriorated painting systems of its steel bridges after the substantial completion of the painting job. Developing a warranty clause to guarantee the quality of painting works has become a mandatory requirement for all future contracts. The introduction of the warranty clause as a part of the contact wording will impose an additional obligation on the contractor for the quality of work performed.

Adopting a total conversion strategy in introducing the warranty clause has its high potential risk. If the developed form turns out to be faulty, the implications can be destructive. A pilot implementation strategy can better fit the development process of such warranty clause. This strategy comprises the development process to take place into successive phases. Initially, a draft of the warranty clause is to be prepared and put into experimental use in the following construction season. Through limiting the implementation of the experimental warranty clause to one pilot project, the consequences of any faulty or insufficient portion of the clause can be confined to that specific project. The performance of the warranty clause in the pilot project will help more identify the possible points of weakness. According to the analysis results, the warranty clause can be modified to better satisfy INDOT's requirements. Afterwards, the warranty clause can be used on a more general basis. However, it will always be subjected to further modifications whenever a certain insufficiency is found out.

3.1 The General Framework

Painting steel bridges constitutes one of a huge variety of practices in construction realm. Each of those practices has its own peculiarities. This raises an important question about the extent to which the various warranty clauses used for each of those practices may differ from each other. It is crucial at this point to realize that the basic structure of any warranty clause is independent upon the specific field of application. However, the basic structure is subjected to all the needed adaptations to fit the specific practice in hand. One of the most explicit differences between any two sample warranty clauses is the part that defines the defects for which the contractor will be held responsible. For instance, the types of defects arising from a poor workmanship in concrete construction are completely different from those associated with painting systems of steel bridges. Whether the warranty clause is designed for concrete construction, painting steel bridges or any other application, it must include a portion that defines: (1) the possible defects that may arise after the substantial completion of works and which relate to the poor workmanship of works, (2) the methodology used for measuring the predetermined defects, and (3) the range of values for which the contractor will be held responsible.

The set of elements generally incorporated in any warranty clause constitutes the aforementioned basic structure or basic model. The similarity in the basic structure highlights the importance of acquiring sufficient knowledge and understanding of the general requirements of any warranty clause. During the development process of the steel bridges painting warranty clause, the predefined framework or structure of the warranty clause will minimize the possibility of any major insufficiency to take place. Added to that, it will help as a baseline for comparison purposes of any existing warranty clauses.

3.2 Various Approaches

There is no single approach that can ideally be followed in developing a new warranty clause for a certain application. The choice itself depends to a great deal on the special circumstances of the development process and the type of data available. When the research was initiated to develop a new warranty clause for steel bridges painting contracts in Indiana, there existed no clear and sound route to follow. However, several approaches were to be considered. Those approaches can be summarized as follows;

(1) To conduct a thorough search for any warranty clause in practical use by another state. If one or more of those warranty clauses are found, they will be subject to a complete review and analysis and, then, adapted in such a way to satisfy the special requirements of INDOT,

(2) To adopt one of the well-established warranty clauses in another painting practice like pipelines, or by the automotive industry. This base warranty clause will be subject to all the necessary modifications to make it match with bridge painting practices,

(3) To start from the basic structure of a warranty clause and develop the applicable form for steel bridges painting practices, and

(4) To collect more information through literature review and analyze the current warranty usage and the impact of warranty applications.

It is obvious that the first alternative is more efficient and economical in terms of both time and effort. This directed the research to find any warranty clause in current use for steel bridges painting practices. A special attention was paid to the neighboring states. The States of the Midwest area have quite similar regional conditions. These regional conditions, however, can play a major role in defining the types of painting failures in the warranty clause wording. As will be discussed in greater detail in the succeeding chapter, the scope of the warranty clause makes up its core element.

3.3 Effectiveness of Web Site Searching

To know the current state of warranty usage on steel bridge painting, each DOT's web site has been searched. All states have their own web sites, and most states have a search function on the main page. In the states that have the function, some keywords like 'Warranty' or 'Bridge painting warranty' were typed to find some information, and in the states that have not the function, some division pages related to bridges were investigated thoroughly. It can be concluded web site searching is not a helpful way because all DOTs do not upload the warranty contracts on the web site even if they have warranty contracts. For instance, Michigan and Illinois apply the warranty to the bridge painting, but their specifications were not found through internet searching. From the web site investigation, MnDOT (Minnesota Department Of Transportation), ODOT (Ohio Department Of Transportation), and UDOT (Utah Department Of Transportation) were found to have their own warranty specifications (See Table 3.1). Among these three DOTs, ODOT solely has a bridge painting specification and uploaded some related files. MnDOT has several warranties, but not in the area of bridge painting. UDOT applies a warranty in the area of roofing. In summary, using an e-mail or a phone inquiring is a more effective way than searching through web sites.

Table 3.1 Bridge Painting Warranty Usage in the U.S. (As of 12/10/01)

State Name	Warranty	State Name	Warranty
AL (Alabama)	NF/NSF	MN (Minnesota)	Several warranty contracts, not bridge painting
AK (Alaska)	NF	MS (Mississippi)	NF
AZ (Arizona)	NF/NSF	MO (Missouri)	NF
AR (Arkansas)	NF	MT (Montana)	NF
CA (California)	NF	NE (Nebraska)	NF/NSF
CO (Colorado)	NF	NV (Nevada)	NF
CT (Connecticut)	NF	NH (New Hampshire)	NF
DE (Delaware)	NF/NSF	NJ (New Jersey)	NF/NSF
FL (Florida)	NF	NM (New Mexico)	NF
GA (Georgia)	NF	NY (New York)	NF
HI (Hawaii)	NF	NC (North Carolina)	NF
ID (Idaho)	NF	ND (North Dakota)	NF
IL (Illinois)	NF	OH (Ohio)	Several warranty contracts including bridge painting
IN (Indiana)	NF	OK (Oklahoma)	NF/NSF
IA (Iowa)	NF/NSF	OR (Oregon)	NF
KS (Kansas)	NF	PA (Pennsylvania)	NF
KY (Kentucky)	NF	RI (Rhode Island)	NF
LA (Louisiana)	NF/NSF	SC (South Carolina)	NF
ME (Maine)	NF	SD (South Dakota)	NF
MD (Maryland)	NF	TN (Tennessee)	NF
MA (Massachusetts)	NF	TX (Texas)	NF
MI (Michigan)	NF	UT (Utah)	One warranty found (Roofing)

VT (Vermont)	NF	WV (West Virginia)	NF
VA (Virginia)	NF	WI (Wisconsin)	NF
WA (Washington)	NF/NSF	WY (Wyoming)	NF

Table 3.1 Bridge Painting Warranty Usage in the U.S. (Cont'd)

(NF: Not Found, NSF: No Search Function)

3.4 Warranty Usage

A warranty is a guarantee of the integrity of a product and of the maker's responsibility for the repair or replacement of deficiencies for several years after the completion of a project (NCHRP Synthesis, 1994). Warranty contracting shifts some post-construction performance risk to the contractor. There are some reasons for states to search for warranty contracting. States had to lower staff and construction costs causing from the government budget reduction. At the same time, the public demands the improved service and performance for its tax amounts.

Warranty contracting was used by the North Carolina Department of Transportation for a pavement marking project as early as 1987. The number of states using warranties has increased since the 1991 Intermodal Surface Transportation Efficiency Act that allowed the use of warranty contracting on projects that are part of the national highway system. At least 23 states are using warranties on construction projects (Russell et al., 1999). The items warranty contracting has been used include asphalt pavement, crack routing and sealing in asphalt pavement, bridge components, bridge painting, chip seals, concrete pavements, concrete pavement patching, ITS components, landscape and irrigation systems, microsurfacing, pavement marking.

Regarding the types of warranty projects completed, Russell et al. (1999) found that there have been about 246 warranty projects since 1987, and more projects have been completed for bridge painting than for any other projects because the Michigan Department of Transportation has required warranties on all bridge painting projects since 1996. Numerous pavement marking and asphalt pavement projects have been also completed in the U.S. using warranties. Other projects do not seem to use warranties actively. The number of warranty projects for bridge painting, pavement marking, and asphalt pavement is 129, 49, 35, respectively. The length of warranties varied ranging from one to five years depending on each DOT's situation.

There are some huddles for state agencies to apply warranties. The major issues are resistance from sureties and contractors, organizational problems, specification development since many items are involved, and so on.

There have been a number of experimental projects and trials for using warranties. Taking a look at efforts undertaken by the following DOTs may be helpful to understand how to use warranties. Their efforts can be described as follows.

Michigan, warranty for bridge painting (Beck, 1998)

As the Department's work force began downsizing, Michigan DOT (MDOT) began looking for alternative inspection ways to reduce maintenance after the completion of painting projects. Performance warranties for bridge painting could be an answer to this problem. In 1989, MDOT experimented with performance warranties to improve the quality of bridge painting operations. Initially, MDOT required a two-year warranty on three structures. With the favorable results from the experimental studies, a technical investigation in cooperation with the Federal Highway Administration (FHWA) was initiated in September of 1990. The objective of the study was to use warranty painting as secondary tool to the Department's normal inspection procedures.

Fifteen warranty and ten control bridges were cleaned and coated. Evaluations were conducted from 1990 to 1996. The two-year warranties were required for the projects, and the 15 percent of the original total contract amount was needed as a supplemental performance bond. After two years, some minor deficiencies were observed and repaired at the contractor's expense. This approach to repair can extend the service life of the coating system and free the MDOT's maintenance crews to perform other urgent preventive maintenance and repairs. In comparing costs between the control and warranty structures, MDOT could not draw definitive conclusions about the impact of the warranty on project costs. Although the control bridges often had similar performance with the warranty structures, the prices for painting the control bridges were equal to or higher than the prices for painting the warranty ones. In addition, there are some benefits from the warranty contracting. The contractor became aware of certain areas that were likely to fail, and the warranty system developed team building and improved communication between MDOT and contractor personnel.

As of September 1996, all of MDOT's new bridge painting contracts contain the performance warranty provision. The required supplemental performance bond has been increased to 20 percent of the original total contract amount from the 15 percent previously.

Wisconsin, warranty for pavement (Johnson, 1999)

The Wisconsin DOT (WisDOT) pavement warranty program began in 1995. Since then, fourteen asphalt concrete and three Portland cement concrete projects have been bid using warranties. The formation of warranty specifications was achieved over two years through the shared efforts of WisDOT and the Wisconsin Asphalt Pavement Association (WAPA), a partnership referred to as WAPA DOT. The Federal Highway Administration's (FHWA) Madison Division Office also played a key role in the process.

WisDOT ask contractors to provide a five-year warranty, and the contractors are responsible for the repairing actions to the deficiencies. Wisconsin's Pavement Distress Index (SPI) was used to establish tolerances for the performance of each pavement. If the tolerances exceed the threshold, then the contractor is required to take a remedial action to correct the situation. Because the contractor has a control of the maintenance on the project for the five years of the contract, the company judges for itself what the level of maintenance should be.

The warranty specifications are designed to allow contractors to have as much freedom as possible. Contractors are fully responsible for and have complete control of the mix design, mix production, traffic control, paving operation and maintenance of the pavement. Wisconsin contractors became innovative and implemented new technology to become more competitive.

To limit litigation on the warranted projects, the specifications call for a Conflict Resolution Team (CRT) to be assembled for each project. The five-person team includes two representatives from the contractor, two from WisDOT and one neutral third party. The cost of the third party is shared equally between the contractor and WisDOT.

The amount of the warranty bond was established by considering the highest reasonable warranty expenditures. A whole pavement could fail in 5 years and require complete replacement, but this is unlikely and would create a very costly bond. The most reasonable scenario is that a thin overlay may be needed, and the warranty bond was based on this assumption.

Washington, warranty for bridge deck expansion joint systems (NCHRP Synthesis, 1994)

This project was awarded in 1991 as part of a bridge replacement project and involves the installation of bridge deck expansion joint systems. Some latitude was granted to the contractor as to the systems selected, but the specifications outlined general administration, material, fabrication, and inspection requirements for the project. The warranty clause required the contractor to provide a five-year written warranty for the operation and durability of the joints. Replacement or repair of any joint parts within the first five years, starting from the date of completion of the contract, was covered under the warranty. The contractor was to replace or repair any joint parts within the period of the warranty at the contractor's expense.

3.5 Foundation of INDOT's Warranty Clause

The investigation into existing warranty clauses for steel bridge painting practices was quite encouraging. IDOT (Illinois Department Of Transportation), MDOT (Michigan Department Of Transportation), and ODOT (Ohio Department Of Transportation) are currently using warranty clauses in their steel bridges painting contracts. MDOT has two versions of the warranty clause that has been used in its contracts. The first version was established in 1989 while the second, which represents an adapted form of the first version, was established in 1994. Those two warranty clauses will constitute the foundation elements of INDOT's steel bridges painting warranty clause. ODOT developed a set of warranty contract documents for implementation in highway construction projects in response to House Bill 163, effective July 1, 1999. ODOT field painting specifications were also prepared at the time. The ODOT warranty clause is quite different from MDOT and IDOT, which will be described in Chapter IV.

IDOT and MDOT warranty clauses represent the basic structure of a warranty clause adapted in such a way to match both the steel bridges painting practices and the special regulations of each of the two DOTs. The initial review showed that certain different clauses exist in terms of the special regulations and permits required. To avoid any possible contradiction in the administrative practices of INDOT compared with those of IDOT, MDOT, and ODOT, INDOT's pavement warranty clause was provided as the third foundation element of the warranty clause. The pavement warranty clause is deemed by INDOT personnel to be among the most successful and well prepared in INDOT practices. The comparative analysis conducted on the material of these five foundation elements helped develop INDOT's painting warranty clause experimentally.

CHAPTER IV
DEVELOPMENT OF WARRANTY CLAUSE

One- or two- year guarantees are not rare in bridge painting specifications today, although the guarantees are often vague and poorly written. These guarantees properly offer little real protection to the bridge authority. The current practices in the United States are still in their infancy. Guarantees are more common in Europe and Japan. In Germany, for instance, large painting contracts have been underwritten by insurance companies as part of a protocol methodology (Hare, 1990.) In spite of the apparent proficiency of some of the guarantees used outside the United States, the full dependency on the foreign practices has its inconveniences. First, the European and Japanese environments in terms of the technical and administrative practices are quite different from those of the United States. Second, lack of communication arising from the language may have its effect on the progress of research work especially with the limited time frame available.

The aforementioned reasons made the other alternative of considering the currently used warranties in the United States, more favorable. To facilitate the development process, a special attention was taken to Indiana's neighboring states. The Midwest area has its unique geographical and environmental conditions. After the substantial completion of the contract works, the deterioration of the painting system can be heavily affected by those conditions. As discussed earlier in Chapter II, the existing environmental conditions play a major role in identifying the painting defects that in term constitute the primary part of the warranty clause.

The search revealed that Illinois DOT (IDOT), Michigan DOT (MDOT), and Ohio DOT (ODOT) are currently using warranties in their painting contracts. IDOT and MDOT are relatively close to each other in content and wording. At least, one of the two warranties was dependent on the other in its development. MDOT was active in the review and modification process of its warranty form. Two different versions of those warranties were available. The first version was established in 1989 while the second was used starting from 1994. ODOT created its own warranty clauses which contain the most detail among the three DOTs. ODOT specifications included many technical aspects as well as warranty items. Unlike MDOT and IDOT, ODOT created contract wording about surface preparation, painting, quality control, safety control, and so on. ODOT warranty specifications can be a good example of integrating many details. It must be borne in mind that such clauses are regarded as the starting point in establishing Indiana's warranty clause. By the end of the data collection stage, the following sets of material were available. Refer to Appendix C for a review of the original forms;

- IDOT provisions for cleaning and painting steel structures with a special provision for performance warranty after the substantial completion of works,
- MDOT special provision for warranting bridge paintings (established in November of 1989), and
- MDOT revised provision for warranting bridge paintings (established in July of 1994).
- ODOT supplemental specification 885 (established in August of 1999)

Although IDOT and MDOT practice with warranties spanned more than 5 years, the degree of success of either of them could not be guaranteed without a continuous review of the warranty performance. Michigan was fast to realize this fact. Two periodical reports were prepared to address this issue since the date the warranty clause was first introduced in a steel bridge painting contract. A copy of the second interim report for the performance of the warranty clause used by Michigan DOT - issued on November 1, 1996 - is included in Appendix D. This report had updated the status of structures completed or inspected since the February 4, 1994 first interim report. At the second report date, all the structures included in the warranty clause performance study had been coated. Because two bridges were coated just before the issuance of the second report, the final report was expected to be written in 1998. This report closed out the research conducted for the performance of the existing warranty clause in MDOT steel bridges painting contracts.

4.1 Preliminary Reviews

Referring to Appendix C, the three forms that present IDOT and MDOT practices resemble each other in many aspects. ODOT has also some same provisions with IDOT and MDOT, but seemed to make much effort to create its own specifications. The major components of the available sets of warranties can be summarized as follows.

- IDOT and two MDOT warranty clauses set the warranty period to be two years. On the other hand, ODOT set the period to be five years, which is three years longer than those of IDOT and MDOT. The wording was so clear that no possible confusion could occur. However, the warranty clauses do not show any distinction in the warranty period for alternate weathering and environmental conditions.

- The defects covered by the warranty clause were defined in four categories. The first two categories handle most of the painting defects' causes that were discussed earlier. Not all the possible causes were included, but the important ones. The third category addresses the coating thickness less than the minimums specified in the specifications. Finally, the fourth category addresses the damages caused by the scaffold removal or other works by the contractor.
- The recognition of defects is the duty of the Engineer. This will be done through the visual inspection and dry film thickness measurement. ODOT specifications describe the repair procedures for the damaged areas and areas which do not comply with the requirements of the specifications. And, ODOT explains the dry film thickness as one of the methods to determine paint thickness in great detail.
- The warranty clauses successfully avoid the possible disputes arising from the previous approval of any parts of the painting works during the contract period. A clear wording is included to clarify the issue.
- IDOT was more conservative in defining the period at which a contractor will complete and submit the repair procedures and progress schedule. IDOT requires the contractor to submit the schedules within 10 working days of notice of defective areas.

- The contractor is required in all four forms to submit proof of a valid liability insurance covering the period of corrective works.
- Realizing that the original contract bonds do not cover the period of corrective works, both IDOT and MDOT require the furnishing of supplemental performance and lien bonds. Generally, the definition of the performance bond is quite clear and complete. It raises no possible conflicts regarding its interpretation. Nevertheless, the portion handling the lien bonds is inadequate in all three forms. This culminates in Illinois practices where neither a description of the submittal procedure nor a defined value of the bond is expressed in explicit terms. The MDOT warranty clause describes the submittal procedure in more detail while lacking any defined value for the lien bond.
- IDOT does not have any conditions about the surety company, but MDOT and ODOT specify some provisions. MDOT requires that sureties must be authorized to do business in the State of Michigan. The sureties that provide bonds are required to have an A.M. Best rating of "A-" or better in the State of Ohio. A.M. Best company offers the comprehensive data about insurance companies, and is recognized as the most authoritative institution being able to provide all insurance company ratings.

4.2 Comprehensive Analysis

The initial review highlights two important aspects. It can be noticed that none of the existing warranty clauses satisfy all the requirements of the basic model of a warranty clause. Among the four forms, the second MDOT and ODOT warranty specifications seem to be well prepared. However, the currently available forms need further adaptations in order to be put into practical use by INDOT. Secondly, permits and administrative practices differ from one Department of Transportation to the other. MDOT has added a supplementary paragraph to its revised form that showed up in 1994 to handle the permits required during the corrective works period.

Therefore, and after discussing the issue with the Study Advisory Committee members of the research project, a recommendation of including the pavement warranty clause used by INDOT was taken into consideration (Refer to Appendix E.). The INDOT pavement warranty clause has been extensively used in the last few years. The successful performance of such warranty clause encouraged the committee members to recommend its use in the development process of INDOT steel bridges painting warranty. At the same time, it will give more insight about the existing practices in Indiana such as the traffic control and right-of-way.

The comparative study has been conducted based on the five available sources of information. To facilitate the analysis, eleven categories were identified. The list includes warranty period, defects definition, inspection schedule, submittal of repair procedure and progress schedule, season of work, liability insurance, traffic control, supplementary performance bond, supplementary lien bond, surety company, and required work permits. The comparative study results are summarized in table 4.1.

Table 4.1 Comparative Study Summary

	Area of Comparison	IDOT	MDOT (November 1989)	MDOT (July 1994)
1	*Warranty Period*	Two years from the date of final inspection by the Engineer.	Same as IDOT. Plus: Two years from the acceptance date of each portion in case of projects that extend over more than two years and work is done in portions.	Same as MDOT (November 1989).
2	*Defects Definition*	a) Four main categories for defining failure types. b) Depends on thickness measurements and visual inspection. c) There are no reference specifications for comparison purposes.	Same as IDOT.	Same as MDOT (November 1989).
3	*Inspection Schedule*	No later than the month before the end of the warranty period. No schedule of inspection is specified.	During the month before the end of the two year warranty period, OR, earlier. No schedule of inspection is specified.	Same as MDOT (November 1989).
4	*Submittal of Repair Procedures and Progress Schedule*	To be submitted in writing within 10 working days of notice of defective areas.	No specific time period from the issuance of notice of defective areas is identified. Only: Submittal is required prior to the start of any work by the Contractor.	Same as MDOT (November 1989).
5	*Season of Work*	Limited to the same season of inspection.	Same as IDOT. Unless the seasonal limitations stated in the painting specifications prevents the completion this season.	Same as MDOT (November 1989).
6	*Liability Insurance*	To be submitted to the Engineer prior to any works.	To be submitted to the Financial Services Division prior to any works.	Same as MDOT (November 1989).
7	*Traffic Control*	No special provision.	The Contractor is obliged to maintain the traffic as described in the original contract documents.	Same as MDOT (November 1989).
8	*Supplementary Performance Bond*	The bond accounts for 15% of the total contract amount. To be submitted upon completion of the work and final inspection of the project. The Engineer withholds in reserve an amount of 15% until the bond is received.	Same as IDOT.	The bond accounts for 20% of the total contract amount. To be submitted upon completion of the work and final inspection of the project. The Engineer withholds in reserve an amount of 20% until the bond is received.
9	*Supplementary Lien Bond*	Not required.	Required for the period on which the corrective work is undertaken. But: No value is specified.	Same as MDOT (November 1989).
10	*Surety Company*	No special provision.	The company must be authorized to do business in the State of Michigan.	Same as MDOT (November 1989).
11	*Work Permit*	No special provision.	No specific provision.	Permit is required with a waiver from any additional fees.

Table 4.1 Comparative Study Summary (Cont'd)

	Area of Comparison	**ODOT**	**INDOT "Pavement Warranty"**
1	*Warranty Period*	Five years from the date of acceptance by the Engineer.	Five years after the date all warranted asphalt is complete. The pavement shall be designed for 15-year lifetime.
2	*Defects Definition*	Same as IDOT.	Not applicable to painting practices.
3	*Inspection Schedule*	During the month before the end of the specified warranty period. Notice: The Contractor should provide inspection equipment.	Initial survey within 45 calendar days after the submittal completion of works. Plus: Annual survey on specific times of the year.
4	*Submittal of Repair Procedures and Progress Schedule*	No specific time period from the issuance of notice of defective areas is identified. Notice: The Engineer shall be given at least two weeks notification before the Contractor begins the corrective work.	No matching provision.
5	*Season of Work*	All paint repair work should be done the same season as the inspection, unless the seasonal limitations of this specification prevent the completion that season. In this case, corrective work should be completed the following season. Notice: All additional defective areas that appear between the time of inspection and the actual corrective work being performed should also be repaired.	No matching provision.
6	*Liability Insurance*	The Contractor is required to maintain the liability insurance.	No matching provision.
7	*Traffic Control*	Traffic control and signing are the Contractor's responsibilities to supply for the period of corrective work. The Contractor's traffic control plan shall be submitted to the District Construction Engineer for approval before inspection is performed.	No matching provision.
8	*Supplementary Performance Bond*	Prior to execution of the contract, and within 10 days of receiving Notice of Award, the successful Bidder shall furnish a contract performance bond and a payment bond, each to be in an amount equal to the Department's estimate. The Contractor shall also furnish a 5-year warranty maintenance bond equal to 100% of the total price as contracted.	No matching provision. Plus: Upon completion of work, the warranty bond becomes effective for a total of 5 years. The bond warrants the proper performance in conducting the repair works in addition to the various payments for the labor, material, and equipment. The bond value is a fixed amount of money.
9	*Supplementary Lien Bond*		
10	*Surety Company*	The Surety that underwrites the maintenance bond is required to have an A.M. best rating of "A-" or better.	The company must be satisfactory to the Department.
11	*Work Permit*	No specific provision.	A Miscellaneous Permit should be obtained from the Department.

Warranty Period

The warranty clause is introduced to warrant the quality of works done by the contractor for a certain period of time following the substantial completion of works. In the Chapter II, the different factors affecting the paint life expectancy were discussed. The two major factors are the environment and the contractor's workmanship. The warranty of the painting system is offered by the contractor to cover his own work. The Department of Transportation should realize that the contractor would not be willing to warrant the painting system for long periods where the environment will definitely affect the system even with an excellent painting job. The most obvious drawback will be the increase in the original contract sum by which the contractor will try to cover those contingencies. The trade-off between the increase in the contract sum due to extending the warranty period and the costs incurred due to the failure of the unwarranted painting system is one of the speculative toughest decisions to be taken by the Department of Transportation.

Both IDOT and MDOT have set a fixed warranty period of two years for the coverage of their steel bridges painting jobs. Although the fixed period cannot be described as simplistic, the expected accuracy and sufficiency are not guaranteed. Correspondence with MDOT revealed that there exists no statistically scientific background for establishing the warranty period. The choice came from the previous experimental projects from which MDOT found that the initial repairs are performed after 2 years. ODOT, however, chose the 5-year warranty period for a bridge painting area.

Currently, INDOT is switching to a new painting specification other than the one in use for the last decade or more. The new painting system consists of organic/inorganic zinc primer, epoxy middle coat, and urethane top coat. According to Hare (1990), the new painting system has an excellent performance in resisting water, UV, alkalies, acidic pollutants, and abrasion. The expected service lives of such system in 1B, 2A, and 2B environments (refer to chapter II for full explanation of the different environment classes) are 35, 13 and 10 years respectively. The service life estimates are based on numerous interviews with highway departments, paint manufactures, contractors, engineers, and other specifying authorities across the country, together with data from a few available published sources. It must be noted that many such sources reflect the use of the same coating in industries other than bridge painting and considerable divergence is possible.

Knowing the lifetime expectancy of the painting system under the different environmental conditions, how can we identify the corresponding warranty period? Answering this question may be tougher than it seems. Since the deterioration of the painting system is non-linear, the determination of the appropriate warranty period depends on the profile of the deterioration curve. Unfortunately, the deterioration curves for many painting systems are not available especially as a function of the various environmental conditions. Thus, the ratio of the warranty period to the paint life expectancy needs to be approximated for practical purposes.

Although pavement practices are quite different from those of painting, the theoretical deterioration curves of each are very similar. INDOT's pavement warranty clause establishes a five-year warranty period for its highway practices. The pavement is commonly designed for periods around 15 years of lifetime. The ratio is roughly one third. Because of the unavailability of the painting deterioration curves, a ratio of 25% - 50% can be used until more statistics about the painting system performance becomes available (Chang et al., 2000).

During the 1997 construction season, there was a decision to apply an experimental warranty clause as part of the contract wording of one pilot project. INDOT Study Advisory Committee members preferred to limit the warranty period to only two years and not to extend it beyond that. On the second interim report prepared by MDOT on the performance of their warranty clause (Appendix D), it is stated that with a two-year warranty period, the warranty provisions do not seem to change the final costs of the contract. However, there is no estimate of the possible drawbacks on the contract sum associated with extending the warranty period beyond that.

For future purposes, the warranty period should correspond to the existing environmental conditions in the area on which the bridge is located. Referring those conditions to one of the predefined environmental classes will help keep the consistency in warranty periods for similar bridges. Warranty periods up to 5 years are expected in those future practices.

The warranty period must start from a fixed point in time. In IDOT warranty clause, the date of final inspection by the Engineer is chosen to represent this reference point. MDOT practice is not much different except for a supplementary sentence to handle the projects that extend over more than one year in contract duration. In such case, the Engineer may accept portions of the painting at the end of each annual work period and the warranty period will start from the acceptance date for each portion, respectively. Without full control of the Engineer, such distinction in contract works may lead to unexpected conflicts. MDOT became aware of that, and therefore, changed the corresponding provision in the revised version of its warranty clause to let the warranty period start from the date of final acceptance of the project regardless of the acceptance date of each portion. This alteration is more conservative than the first version.

Defects Definition

The core element of the warranty clause is to define the various defects that arise from the poor workmanship of the contractor and against which the warranty clause warrants the Department of Transportation. Without a clear definition, as much as possible, conflicts may occur between the two parties. At the same time, and as explained before, any explicit bias from the Department of Transportation will result in an increase in the contract sum by which the contractor tries to cover those apparent contingencies.

IDOT, MDOT, and ODOT use almost an identical form to identify the painting defects. Four different categories are included:

1. The occurrence of visible rust or rust breakthrough, paint blistering, peeling or scaling.
2. Paint applied over dirt, debris, blasting debris, or rust products not removed during blast cleaning.
3. Incomplete coating or coating thickness less than the minimums specified in the painting specifications.
4. Damage to the coating system caused by the contractor while removing scaffolding or performing other work.

It is important that three DOTs raise an important cause of painting failure that is rarely mentioned in literature. That is the damage of the coating system emerging from the reckless removal of scaffolding after the final inspection by the Engineer.

Comparing the composition of this part of the warranty clause with the basic model previously, it can be easily noticed that it lacks two requirements. The basic model requires - in addition to a clear identification of defects - both a well-defined method of measurement for those defects and the range for which the contractor will be held responsible. Unfortunately, the second and third portions are not included.

Correspondence with MDOT revealed that the generalized definition of defects is established to warrant the work regardless of the actual cause of deterioration. If a certain defect emerges during the warranty period, the contractor has to return to site and fix such defect. Considering the limited warranty period of two years, it is admitted that such generalization is reasonable. It is rare that unexpected and fast deterioration can happen in the first two years even with a severe weathering and/or environmental conditions. The only side effect of this generalization is the increase of the contract sum used by the contractor to cover any future contingencies. However, this possible increase is expected to be minimal due to the fact of the limited warranty period. The second interim report prepared by MDOT (Appendix D) states that there was no correlation between cost and the warranty provision use in that particular form. It also adds that a warranty is just one of many factors that determine the final project cost, such as time of year, how busy the contractor is, etc.

INDOT policy is to use the two-year warranty period for the experimental pilot project. Afterwards, the warranty period will be extended depending on the performance of the warranty clause in the pilot project and the data available on the new painting system. Although the previous definition of defects may seem reasonable for a two-year warranty period, it will become totally insufficient for extended periods. This part must be redeveloped to contain all three portions required for an ideal warranty clause.

Because of severe rainfall, hail and/or wind, the surface of the paint may be aggravated such that its thickness becomes less than the value in specification. The degree of erosion of exterior paint can be evaluated using ASTM-D 662 standards. Without the existence of such case, the over-thinned or -thick dry film thickness can be unquestionably referred to the poor workmanship of the contractor. The readings of the dry film thickness are usually taken using magnetic gages. To identify the status of the paint thickness, SSPC-PA 2 was developed. The specifications state that five separate spot measurements should be made over every 100 square foot. Each spot measurement consists of an average of three gage readings next to one another. The contractor's work will be considered satisfactory *if and only if* the average of the five spot measurements are within the specified thickness, while single spot measurements are permitted to be 80% of the specified thickness.

Referring to chapter II, a certain category was identified where the corresponding defects of this category arise from the deficient surface preparation. Those defects are mostly the contractor's responsibility. The list includes blistering, peeling, scaling, and undercutting rust. This gives INDOT more freedom to generalize the definition of the aforementioned defects.

In case no apparent adhesion problem exists, the degree of adhesion of the coating to the substrate can still be evaluated using ASTM-D 2197 (Adhesion by scratching or scraping) and/or ASTM-D 3359 (Adhesion by tape test). The specifications support the idea of the expected life time of the existing paint system depending on the results of the test. The acceptability of results is based upon 95% confidence level. Refer to Appendix O for a copy of the test methods and procedures. If any of the various adhesion problems resulting from the poor surface preparation occurs, the responsibility of the contractor is more obvious. The list includes peeling, blistering, scaling and undercutting rust. Unfortunately, the only standard available for measuring the degree of severity in this category is the one associated with blistering. Appendix E contains a copy of the standard procedure ASTM-D 714 for measuring the degree of blistering of paints. The test method employs photographic references to evaluate the degree of blistering deterioration.

The aforementioned forms of deterioration are easier to judge by the inspector since the effect of the poor workmanship far exceeds the effect of the environment in developing them. Unfortunately, this does not include one of the most widespread and detrimental form of paint deterioration, or in other words, rusting. The second interim report on the performance of warranty clauses in painting practices prepared by MDOT (Appendix D) shows pinpoint rusting as the major deterioration form noticed during the two-year warranty period. The danger of rusting is associated with the fact that it attacks the substrate and causes the steel to corrode and then a reduction in the steel sections occurs.

The difficulty in determining what stimulated the rust to occur is that both the poor workmanship and the severe environmental effects incorporate together in its development. This even happens with different degrees from one section to another on the same bridge. Sometimes the deficient design on special sections of the bridge subjected to settled water or continuous leakage leads to excessive rusting on those specific areas. The emergence of the set of problems related to the location, design, or use of the bridge should attract the attention of the Department of Transportation to their long-run effects on the life expectancy of the bridge itself.

Whenever no apparent cause of rusting beyond the contractor's control exists, the poor workmanship rises as the major cause. The improper mixing and application of the paint can easily cause the water to penetrate the painting system to the underneath steel substrate and start the rust. ASTM-D 610 standard covers the evaluation of the degree of rust on a painted surface using visual standards (Appendix O). The visual standards were developed in cooperation with the Steel Structures Painting Council (SSPC) for the further standardization of the procedure. The rusting measurement depends on the comparison between the inspected bridge and a set of photographic reference standards to determine the percentage of the area rusted.

Eleven different ratings are identified in the evaluation procedure. The grade 10 means no rust, and the grade 0 means 100 % rust. The corrosion performance rating system is based on visual inspection; therefore, variations can occur between different inspectors. In addition, visually quantifying the amount of corroded area can be very difficult even for a well-trained inspector. To reduce the amount of discrepancy in the data collection, Tam and Stiemer (1996) recommended the use of a set of photographs showing different corrosion ratings on actual bridge components with schematic representation of the ASTM-D 610 standard. Furthermore, in their development of a bridge corrosion cost model, they approximated the area to be repainted as a function of the rating given by ASTM-D 610. Table 4.2 represents the values used in developing the cost model;

Table 4.2. Estimated Area to be Repainted (Tam and Stiemer, 1996)

Corrosion rating	Description	Area to be painted (%)	Rust percent range (x)
10	No rust or less than 0.01% rust	0	$0 \leq x < 0.01$
9	Minute rust, less than 0.03% rust	0	$0.01 \leq x < 0.03$
8	Few isolated rust spots, less than 0.1% rust	0	$0.03 \leq x < 0.1$
7	Less than 0.3% rust	0	$0.1 \leq x < 0.3$
6	Extensive rust spots, less than 1% rust	8	$0.3 \leq x < 1$
5	Less than 3% rust	18	$1 \leq x < 3$
4	Less than 10% rust	40	$3 \leq x < 10$
3	Approximately 1/6 of surface rusted	60	$x \cong 16.7$
2	Approximately 1/3 of surface rusted	100	$x \cong 33.3$
1	Approximately 1/2 of surface rusted	100	$x \cong 50$
0	Approximately 100% of surface rusted	100	$x \cong 100$

Identifying both the type of defect and its method of measurement leaves us with the range for which the contractor will be held responsible for the rusting of the bridge surface. Comparing the different values of the areas to be repainted corresponding to the corrosion ratings, it can be noticed that no repair work is required in case of rust less than 0.3% of the area. Although no explanation is given, it is believed that conducted repair for rusted area less than 0.3% is unrealistic. If the rust is spread over large areas with this minimal ratio, it will become almost impossible to identify a certain area to be repainted. Added to that, the unreasonable interruption to the traffic and the possible damage to the existing paint resulting from erection and removal of scaffolds may become more costly and time consuming to the Department of Transportation.

Discussions with INDOT Study Advisory Committee members led to review of the AASHTO requirements for the inorganic zinc primer where a maximum ratio of 1%

rusting is allowed in a three-year period after the substantial completion of all contract works. It is worth mentioning that the AASHTO specification M300 (Section 4.7) allows 1% rusting in coastal and marine environments that are the most harsh in all possible environments. This environment is equivalent to 2B as defined by Hare (1990). The system composed of organic/inorganic zinc as primer coat, epoxy as mid coat, and urethane as top coat is regarded as one presently being put into broader use by INDOT. This stimulates increasing the warranty period for values up to 5 years in mild environments with a maximum of 1% rusting in case of adopting such a system. However, the various coating systems under study characterize long lifetime expectancy that in turn encourages using an allowed rusting below 1%. The ratio can be accustomed to varying possible warranty periods; each corresponding to a class of environment as defined in an earlier chapter.

Inspection Schedule

The schedule of inspection determines when the painting works will be inspected for defects. The inspection schedule, in general, is dependent upon the inspection policy of the Department of Transportation and the warranty period. IDOT does not specify a certain inspection schedule as the corresponding provision states that "*The Engineer will inspect the bridge thoroughly for the paint system defects no later than the month before the end of the warranty period*." The decision is left for the Engineer to choose the most appropriate time to conduct the inspection process. His decision will basically depend on his judgment on the performance of the painting system.

MDOT is more specific in identifying the inspection schedule. The painting system is to be inspected during the month before the end of the warranty period, i.e., the last month of the warranty period. Although this schedule is more specific, it can have a detrimental effect on the bridge in case of a quickly deteriorating painting system. Realizing this fact, MDOT adds a supplementary part to allow for earlier inspections to take place whenever the Engineer feels there is a need for such inspection of the painting system. For a complete control of the inspection process, MDOT notifies the contractor that the inspection process will be done using Department maintenance personnel and equipment.

ODOT also specifies the inspection schedule. The state of painting should be checked during the month before the end of the specified warranty period. Moreover, ODOT requires contractors to furnish, erect, and move scaffolding and other appropriate equipment, and meet the appropriate safety requirements from the Ohio Industrial Commission and the Occupational Safety and Health Administration (OSHA).

There is no ideal arrangement for the inspection process since it depends to a great deal on the administrative practices of the Department of Transportation, as aforementioned. Discussions with the members of INDOT Advisory Committee and the thorough review of the pavement warranty clause revealed that INDOT follows a different policy in conducting its inspection after the substantial completion of works.

INDOT's pavement warranty clause requires an initial pavement condition survey to be conducted 45 calendar days after the substantial completion of the project. Afterwards, an annual inspection takes place at predefined times of the year with no cost to the contractor. In addition, a final inspection occurs just before the end of the warranty period. It can be noticed that the pavement warranty provides an extensive inspection policy. One of the obvious reasons is that the warranty period for INDOT’s pavement warranty extends for 5 years while the corresponding warranties for painting practices in Michigan and Illinois span for only 2 years. At the same time, the defects in the pavement works can cause serious safety problems to the highway users which is not the case for painting practices.

For painting practices, INDOT has a continuous inspection policy for its steel bridges. Every bridge in Indiana is inspected for the quality of painting every two years. After the thorough examination of the bridge, it is rated for the paint quality on a 0-9 scale where "0" represents the worst quality and "9" the highest. The existing data is very helpful in developing the deterioration curves for the existing painting systems. Because of the recent change to the organic/inorganic, epoxy, urethane system, there exists inadequate data to verify the previous figures given by Hare (1990). However, the biannual inspection policy of INDOT will generate enough information for creating deterioration curves for the changed painting system.

Submittal of Repair Procedure and Progress Schedule

During the usual course of the original contract works, the contractor is required to submit to the Engineer a progress schedule with a detailed procedure description. The progress schedule identifies the different jobs he is going to perform with the logical sequence of those jobs. The Engineer must approve all of those plans in writing before the start of works. When the Engineer finds that some of those jobs are not properly planned, he notifies the contractor with all the corrections that should take place.

The repair works are by no means different. The contractor is bound to perform the works under the same conditions of the original contract. Therefore, he is required to submit a detailed repair procedure and progress schedule to the Engineer for review and approval. The submitted plans form a guarantee of the contractor's willingness to perform the repair works properly. However, the correspondence of plans and formal letters has been always a major cause of delay in the construction industry. Sometimes the process is abused to postpone the date of the start of works.

The provision handling the submittal of the repair procedure and progress schedule has a double benefit. First, it guarantees the proper execution of repair works since all repair plans will become available to the engineer before the start of repair works. Consequently, he will be able to make all the needed corrections and clarify the possible conflicts that may occur. Secondly, setting a strict period for the preparation of the progress schedule could save the Department of Transportation a lot of wasted time. Under this provision, the contractor will be prohibited from extending the period for long periods without an apparent reason.

MDOT provision states, "*The repair procedures and progress schedule shall be submitted in writing to the Engineer for review and approval prior to any work.*" However, there is no restriction on the period in which the contractor is supposed to get it done. IDOT extends its provision to enforce the repair procedure and progress schedule to be submitted within 10 working days of notice of defective areas. ODOT explains this issue more clearly than the other two states by addressing that the Engineer shall be given at least two weeks notification before the Contractor begins the corrective work and shall be allowed full inspection of all operations at the Contractor's expense.

A question may arise about the validity of establishing a certain period to prepare the repair procedure and progress schedule while the size of work can substantially vary from one project to another. This is true to some extent. If the size of the project is huge such that it takes more than a year in contract period, it will be unrealistic to crunch the period allowed for preparing the repair schedule to only ten days. The period needed for revising and approving the schedule may drastically increase because of all the conflicts need to be cleared. The Department of Transportation should handle the issue more flexibly depending on the size of the project itself. The period given for preparing the progress schedule is recommended to vary according to the size of the project from one to three weeks. The value used for the attached draft at the end of the chapter is left as ten days for explanation purposes but it must be kept in mind that this value should vary according to the size of the project.

Season of Work

When the Engineer that requires an immediate repair action identifies certain defects, the contractor is entitled to perform the corrective works as soon as possible. Any delay in conducting the corrective works will have a negative effect on the existing paint in the defected area and consequently the underlying substrate. To ensure quick action, IDOT, MDOT, and ODOT enforce the corrective works to take place within the same season on which the bridge was inspected by the Engineer. This is identified by the sentence: "*All paint repair work will be done by the same season as the inspection*."

The Engineer has the complete freedom to choose when to conduct his inspection. Sometimes, he takes such an action far before the end of the warranty period whenever a severe deterioration of the painting system has been noticed. However, in reality, the corrective works cannot be conducted all over the year. Generally, most painting systems are sensitive to temperature and humidity. The specifications usually determine the ideal range of temperature and humidity at which the painting system can be applied. The same range, of course, is valid for the repair works. Under the severe weathering conditions, the painting material cannot be prepared or applied properly. Taking into consideration the occasional conflicting weathering conditions in the Midwest area, MDOT and ODOT added a supplementary sentence to the previously quoted one to cover such an occasion. Thus the Contractor is obliged to take an immediate action such that the corrective works be done the same season unless the seasonal limitations stated in the painting specifications prevents the completion that season. In this case, the corrective work will be completed the following season.

Reviewing INDOT pavement warranty clause showed no matching sentence that has the same meaning. However, this is not an issue since the pavement warranty clause obligates the contractor to take an immediate action within 24 hours if a safety problem is discovered in the pavement works. Assuming that the Engineer responsible for the inspection process is aware of the effects associated with a badly deteriorated painting system, it is of low possibility that the deterioration of the painting system may cause such a safety problem. Regarding the effect of weather on continuity of works in the same season, the pavement materials are less vulnerable to the weather conditions than paints. Therefore, delaying the works for long periods as those required for painting systems is impractical.

Discussions with INDOT Advisory Committee members pinpointed that on many occasions, the works were delayed because of the inconvenient weathering conditions. It was obvious that the supplementary part added by MDOT and ODOT can save any conflicts arising from such an issue.

Liability Insurance

This type of insurance protects against legal liability to the public (Fisk, 1997.) All owners require their contractors to submit such an issuance before the start of the original or repair works. The purpose of the liability insurance is to avoid any legal problem with a third party that may arise from the construction works. This insurance was not introduced as a part of the basic model of a warranty clause because it is always submitted to the owner in case of any construction activity.

Fisk (1997) explains that the contract documents should require that evidence of specified insurance be submitted. There are many forms of liability insurance, but the one usually recommended for construction is the Broad Form Comprehensive Liability Policy. Under this type, all forms of liability insurance are combined into one contract.

IDOT, MDOT, and ODOT require contractors to maintain the liability insurance prior to any works. The liability insurance is in effect during the period the corrective work is being done. However, there is a difference in identifying the person or entity to whom the contractor is to supply the verification of the liability insurance. IDOT requires the verification to be submitted to the Engineer while MDOT requires it to be submitted to its Financial Services Division. The distinction by no means changes anything in the validity of the submittal process since it depends on the inherent regulations of each department. The existing practice of INDOT in its current painting contracts is to represent INDOT by itself, i.e., all verifications are to be submitted to the name of INDOT regardless the person or entity that officially represents INDOT at that time. Presently, the INDOT Contract and Construction Division handles all the construction projects.

Traffic Control

During the execution of repair works, the traffic may become obstructed because of the contractor's equipment and/or labor. In such occasion, the flow of traffic on the bridge and sometimes the reach of the highway on which the bridge is located might be affected. It is important for the Department of Transportation to guarantee that such interruptions for the traffic are limited to the lowest possible levels. Otherwise, further considerations are to be taken which sometimes require detouring this portion of the highway. These circumstances are not common in painting practices as much as highways' construction and rehabilitation. However, the Department of Transportation must be cautious to these possible occasions.

When the second version of MDOT warranty clause was introduced, a supplementary provision was added to handle this issue. There is no matching provision in Illinois practice. MDOT provision states, "*When completing any identified corrective work, the contractor shall maintain traffic as described in the original contract documents*." ODOT expresses that the contractor is not only responsible for the traffic control and signing during the period of corrective work, but shall submit the traffic control plan to the District Construction Engineer for approval as well.

The provision of traffic control perfectly addresses the problem such that the contractor is obliged to perform work in full accordance with the original contract documents. However, the wording itself can cause legal conflicts. It is not uncommon that specifying a certain requirement out of a whole set of requirements may be interpreted such that it is the only one valid under the new circumstances. In reality, the Department of Transportation needs the contractor to comply with all the original contract provisions and rules with special emphasis on the importance of traffic control. The original contract documents that are used by INDOT usually include various requirements other than the traffic control. For example, a special provision is commonly included in the original contract documents to provide the contractor agreement to comply with all federal, state and local laws, rules, regulations, or ordinances.

Supplementary Performance and Lien Bonds

Issuance of bonds, that ensures the owner against all possible contingencies associated with the execution of the contract or warranty works, is a common practice in almost all construction-related projects. Conflicts that arise from this issue emerge from the ambiguous issuance procedure, improper bonds value, and rejection of the surety company or the form used. All matters related to the surety company will be discussed in more detail in a succeeding section.

As explained earlier in chapter III, there exist two types of bonds required for the warranty of painting works; i.e., supplementary performance bond, and supplementary payment bond. IDOT requires only a supplementary performance bond to be furnished to the Department. The bond is in the sum of 15 percent of the of the original total contract amount. The bond will be in force for the period covering the two-year warranty period and the time required to perform any corrective work covered by the warranty. To ensure the proper issuance of the supplementary bond before the final inspection by the engineer, an amount of 15 percent of the total contract sum will be withheld until the engineer has received the supplemental bond.

Although IDOT does not require a supplementary payment bond, which can be considered a major defect in its warranty clause, the construction of the part associated with the supplementary performance bond is quite integrated. It satisfies all the basic requirements including the issuance procedure, the bond value, and the items covered by the bond. Moreover, IDOT realized the possible future conflicts arising from the elusive wording of the bond itself. This stimulated adding a provision that limits the supplementary performance bond to the form prepared by the Department.

MDOT has almost the same form for requiring the supplementary performance bond. The only difference is that the value of the bond was raised from 15 % to 20 % in the second version of the warranty clause. No reason was apparent for this growth of the bond value. Also, all correspondence with MDOT did not reveal the reason behind the change. Regarding the supplementary lien bond, a special provision associated with this bond is added in the MDOT warranty clause. If, after the inspection process during the warranty period, a specific corrective work is required, the contractor should submit a supplementary lien bond to MDOT that is in effect for the duration of the corrective work. Again, the special form of this lien bond is limited to the one prepared by the Department. Although MDOT does not have the same defect of ignoring the supplementary lien bond in its clause, the form is unclear and ambiguous. The MDOT warranty clause fails to identify a specific value of the supplementary lien bond. The special provision stating the two bonds to be satisfactory and acceptable by MDOT cannot compensate the elimination of the lien bond value. If it does, therefore, there is no need to define a value for the performance bond too.

ODOT stipulates that the successful Bidder shall furnish a contract performance bond and a payment bond prior to the execution of the contract and within 10 days of receiving Notice of Award. The amount of two bonds shall be equal to the Department's estimated one. In addition to the performance bond and the payment bond, ODOT requests that the contractor shall furnish a 5-year warranty maintenance bond equal to 100 % of the total price.

INDOT pavement warranty clause has different practice in terms of the definition of performance and lien bonds. INDOT eliminates the differentiation between the two common bonds. In other words, the pavement warranty clause requires the contractor to submit to the Department of Transportation a warranty bond for a defined amount of money. This warranty bond warrants both the performance and payments to whoever cooperated in executing the repair works. This change from the traditional representation of contract bonds, however, requires a clear definition of the items covered by the bond. An explicit provision states, "*The bond is intended to ensure completion of required warranty work, including payments for all labor, equipment, and material*." This inclusion simply extends the coverage of the warranty bond to include, in addition to the ordinary performance requirements, the payments for labor, equipment and material which constitute the core of the lien bond.

There is no standard form that can ideally be used to express the procedure and quantity of the warranty bond. Whether the warranty bond is identified as a single entity or two entities where the first covers the performance and the second covers the payments, the main point is that the warranty bond definition should be unambiguous in terms of coverage, issuance procedure, and amount. INDOT's pavement warranty clause offers a clear and condensed provision that is more appealing to be used in painting practices. However, the use of a pre-defined ratio seems more realistic for this practice since painting projects can differ substantially in contract value. INDOT's Advisory Committee members reached a consensus on the ratio of 50% to represent the warranty bond value. At this point, it is hard to predict whether this amount is satisfactory or not. The final decision will depend on the feedback from the various projects composing the first phase of practically implementing this warranty clause.

Surety Company

The surety company constitutes the entity that guarantees the proper execution of works to the satisfaction of the Department of Transportation. The contractor may become unable to perform the repair works or pay his material, equipment, or labor suppliers because of any financial difficulties. Under those circumstances, the Department of Transportation can benefit from the existing bonds to get the work done or to relieve them from any external obligations to a third party who shares in the execution of repair works.

Without the support of a reputable surety company, the Department of Transportation may encounter unexpected losses. Therefore, the Department must be cautious in accepting the bonds and the surety company issuing them. Any reader of the warranty clause implicitly interprets the acceptance of the surety company by the Department of Transportation if the clause does not state it explicitly. However, the explicit wording prevents any possible future conflicts.

IDOT warranty clause does not enforce the acceptance of the surety company in explicit terms while both MDOT and ODOT painting warranties explicitly stipulates that. ODOT warranty specifications state that the sureties are required to maintain an A.M. Best rating of “A-“ or better. ODOT does not hold the right to choose an applicable surety company by following the evaluation of a trustable company. MDOT, however, requires that the company must be authorized to do business in the state of Michigan. It is believed that this addition by Michigan is not essential since the final decision about accepting or rejecting the surety company will remain in the hands of the Department of Transportation. Although this limitation may help in reducing the possible risks from out-of-state contractors, it may prevent many competent contractors who are willing to open a new market to bid the project.

Work Permit

Each Department of Transportation sets its own local regulations. This item, therefore, is not comparable between the different Departments. Generally, highway-related projects such as pavement and steel bridges painting cause certain interruption to the traffic flow. So as to be allowed to do so, the contractor is required to get certain permit(s) from the Department.

There is no explicit provision for such requirement in IDOT's, the first version of MDOT's, and ODOT's warranty clauses. However, the second version of MDOT warranty clause adds a provision that requires the contractor to apply for a permit to work within MDOT right-of-way. Again, this provision corresponds to Michigan policy. INDOT pavement warranty clause requires that "*Prior to proceeding with any warranty work or monitoring, a Miscellaneous Permit shall be obtained from the department*." Discussions with INDOT Advisory Committee members lead to a consensus on adopting the same policy for painting practices.

4.3 Proposed Warranty Clauses

After examining the above parameters and issues, the warranty clauses can be suggested in the Table 4.3 for INDOT implementations. The reader can find the differences between the one first proposed in January, 1999 and the one proposed at the conclusion of the research project in June, 2003.

Table 4.3 Proposed Warranty Clauses

	Area of Comparison	INDOT Proposal (January 1999)	INDOT Proposal (June 2003)
1	*Warranty Period*	Ratio from the paint expected lifetime under the existing environmental conditions of the area. <u>Note</u>: Two years for experimental purposes.	Ratio from the paint expected lifetime under the existing environmental conditions of the area. <u>Note</u>: Five years for large-scale implementation.
2	*Defects Definition*	Six main categories of defects definition. Depends on thickness measurement and visual inspection. Contains references specifications from ASTM and SSPC for comparison purposes.	Six main categories of defects definition. Depends on thickness measurement, rust percentage, and final visual inspection. Contains references specifications from ASTM and SSPC for comparison purposes.
3	*Inspection Schedule*	Biannual regular inspection. <u>Or</u>, at any time the bridge coating system requires immediate remedies.	During the month before the end of the specified warranty period, biannual regular inspection, or, at any time the bridge coating system requires immediate remedies. <u>Notice</u>: The Contractor should provide inspection equipment.
4	*Submittal of Repair Procedures and Progress Schedule*	To be submitted in writing within 10 working days of notice of defective areas.	To be submitted in writing within 10 working days of notice of defective areas.
5	*Season of Work*	Limited to the same season of inspection. <u>Unless</u> the seasonal limitations stated in the painting specifications prevents the completion this season.	All paint repair work should be done the same season as the inspection, unless the seasonal limitations of this specification prevent the completion that season. In this case, corrective work should be completed the following season. <u>Notice</u>: All additional defective areas that appear between the time of inspection and the actual corrective work being performed should also be repaired.
6	*Liability Insurance*	To be submitted to INDOT Operations Support prior to any works.	To be submitted to INDOT Contracting Department prior to any works.
7	*Traffic Control*	The Contractor shall comply with all regulations described in the original contract documents such as, but not limited to, the maintenance of the traffic.	Traffic control and signing are the Contractor's responsibilities to supply for the period of corrective work. The Contractor's traffic control plan shall be submitted to the District Construction Engineer for approval before inspection is performed.
8	*Supplementary Performance Bond*	Same as INDOT pavement warranty clauses. <u>Except</u>: Warranty value = 20% of the total contract amount. The value is subject to increasing if needed in the future.	Prior to execution of the contract, and within 10 days of receiving Notice of Award, the successful Bidder shall furnish a contract performance bond and a payment bond, each to be in an amount equal to the Department's estimate. The Contractor shall also furnish a 5-year warranty maintenance bond equal to 50% of the total price as contracted. The value is subject to increasing if needed in the future.
9	*Supplementary Lien Bond*		
10	*Surety Company*	The company must be satisfactory to the Department.	The Surety that underwrites the maintenance bond is required to have an A.M. best rating of "A-" or better.
11	*Work Permit*	A Miscellaneous Permit should be obtained from the Department.	Prior to proceeding with any warranty work or monitoring, a Miscellaneous Permit should be obtained from the Department.

4.4 Other Issues

The comparative study presented in the previous section sets the grounds for establishing the first and second version of INDOT steel bridge painting warranty clauses (Refer to Appendix A and B). Many pilot projects and much discussion are recommended in order for the initial warranty clause to put into practice. From the previous comparative study, several issues can be drawn to make better warranty specifications.

First of all, the scope of warranty should be clearly determined. IDOT and MDOT focused on the warranty itself, but ODOT mentioned various aspects regarding bridge painting as well as warranty items. ODOT warranty clauses describe the methods and procedures of surface preparation, painting, quality control, and so on. The warranty clauses are more comprehensive and specific. However, too detailed specifications could inhibit the innovative solutions of contractors. It may be necessary that a warranty program be set up to give contractors as much freedom as possible within the given specifications. The specifications can allow contractors to select paint materials, painting techniques, and quality control program. In fact, WisDOT believes that its pavement warranty shows good performance by giving contractors much freedom like mix design, mix production, traffic control, and paving operation (Flynn, 1995).

Second, a Conflict Resolution Team (CRT) may be necessary for the warranty clauses. A CRT is needed for items that have many possible causes of failures and are difficult to determine a correct cause like chip sealing or microsurfacing. Bridge painting or pavement marking, however, may not require a CRT because the failure causes are identifiable clearly (Johnson, 1999).

CHAPTER V

NEURO-FUZZY RECOGNITION APPROACH (NFRA)

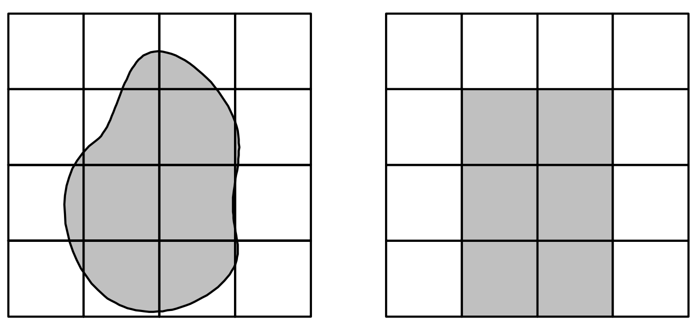
This chapter presents the theoretical background and framework of the neuro-fuzzy recognition approach (NFRA) and its applications (Chen, 2001).

5.1 General Description

Poor image quality is always a tough problem to digital image recognition. New methods have been developed and proposed in order to deal with the difficulties associated with digital image recognition, such as effects of shadows and over-illumination. In this chapter, a new image recognition approach that combines the artificial neural network and the fuzzy logic system is proposed and introduced.

The utilization of artificial neural networks for image recognition is not a new idea. Because of their intelligent and learning features, different kinds of artificial neural networks have been used for the image recognition purpose. In civil and construction engineering, AbdelRazig proposed a hybrid model, which made use of artificial neural networks, for the defect recognition of steel bridge painting (AbdelRazig 1999). This was a great idea and could automate the inspection process of steel bridge painting. However, like every other model, it still contains some deficiencies. This model functioned well with good quality images, but had problems handling non-uniformly illuminated images.

The neuro-fuzzy recognition approach (NFRA) proposed in this chapter is devoted to the recognition ability on non-uniformly illuminated images. It segments an image into three different areas in accordance with the illumination of the pixels in the image, and then processes the image based on each area. The artificial neural network used in this approach automatically generates three threshold values with three illumination values as the input. The fuzzy logic system will be used to deal with the boundaries between areas. In a digital image, data are stored and presented with numerous small square cells (or pixels). Information stored in a single cell is either “all” or “none”, with no partial existence allowed (See Figure 5.1(b)). However, in the real world, an original image may take some partial cells, as presented in Figure 5.1(a). Thus, an original image as shown in Figure 5.1(a) may be stored as a digital image like Figure 5.1(b). Although these differences are hard to be distinguished by human eyes, they do exist. In order to smooth the information stored along the boundary, the fuzzy theory was utilized to adjust some features of the cells along the boundary, such as the gray level values. Details about the framework of this approach are described in the following sections.



(a) Original image data (b) Stored digital image data

Figure 5.1 Comparisons of Image Data

5.2 Theoretical Background

This section introduces the theories used in the neuro-fuzzy recognition approach (NFRA). They include artificial neural networks, fuzzy logic systems, the K-means algorithm, and image thresholding.

5.2.1 Artificial neural networks

Artificial neural networks are memory-based technologies that can accumulate past experiences through the process of training to make human-brain-like decisions and judgments. It has been widely used in academics and industries. Its applications can be found in the areas of pattern recognition, nuclear reactor simulation, image processing, differential equation solving, and so forth. The human-brain-like characteristic makes artificial neural networks "intelligent" and thus, it is considered as a kind of "artificial intelligence (AI)."

5.2.1.1 Features of artificial neural networks

Compared with other artificial intelligence (AI) technologies, artificial neural networks have some significant features that make them powerful tools in decision support applications. Generally, artificial neural networks have the following inductive features (Tsoukalas and Uhrig 1997):

- Their learning ability helps them learn from past experience through the process of training.

- Their special distributed and associative memory makes them able to come up with the optimal and closest results even with partial inputs, and thus, makes them fault-tolerant.

In the training process of an artificial neural network, information of the training examples will be stored in all the weights throughout the network. Thus, in a trained artificial neural network, a missing message in the input is possible to be recovered by the other input messages as well as the information stored in the weights, and a proper output can still be expected. Detailed description about artificial neural networks is made in the following sections.

5.2.1.2 Artificial neurons

Artificial neurons are the basic components in an artificial neural network. An artificial neuron collects signals in the receiving end and send out the filtered signal in the outgoing end. Figure 5.2 depicts the structure of a typical artificial neuron (Tsoukalas and Uhrig 1997):

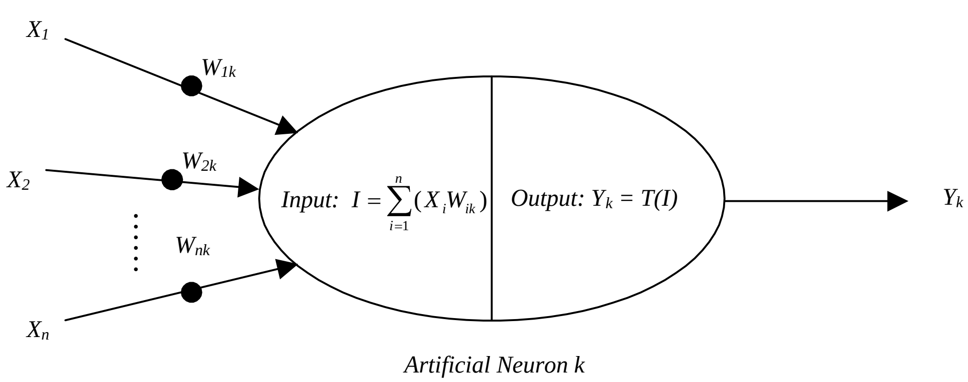


Figure 5.2 Structure of Artificial Neuron

The receiving end has incoming signals X_1, X_2, …, and X_n. Each of them is assigned a weight, which is given based on experience and may change during the training process. The summation of all the weighted signal amounts gives the combined input quantity I. The combined input quantity I is then sent to a pre-selected transfer function (sometimes called an activation function) T, and a filtered output Y_k is generated in the outgoing end of the artificial neuron k through the mapping of the transfer function.

There are several types of transfer functions. The most used transfer functions are the sigmoid function, and the threshold function. The sigmoid function is a continuous function that varies between two asymptotic values, usually 1 and –1, or 1 and 0. The sigmoid function can be represented by the following equation (Tsoukalas and Uhrig 1997):

$$T(I) = \frac{1}{1+e^{-\phi I}} \tag{5-1}$$

where ϕ is a positive scaling constant, which controls the steepness between the two asymptotic values. Figure 5.3 depicts the sigmoid function (Tsoukalas and Uhrig 1997). The threshold function passes 1 as the output if the input is greater than the threshold value. On the contrary, if the input is less than or equal to the threshold value, the threshold function will pass 0 or –1 as the output, as indicated in Figure 5.4 (Tsoukalas and Uhrig 1997).

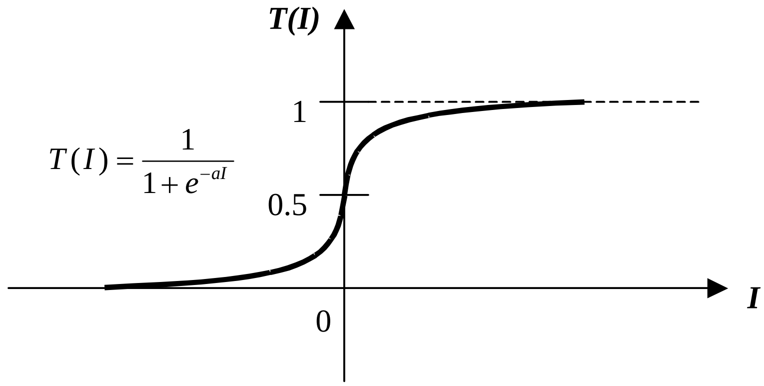
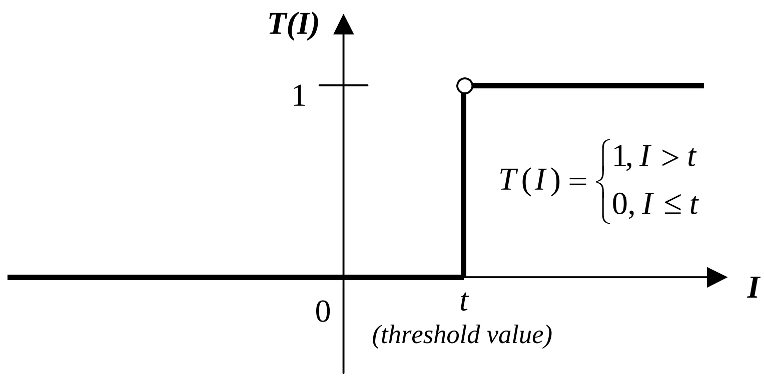
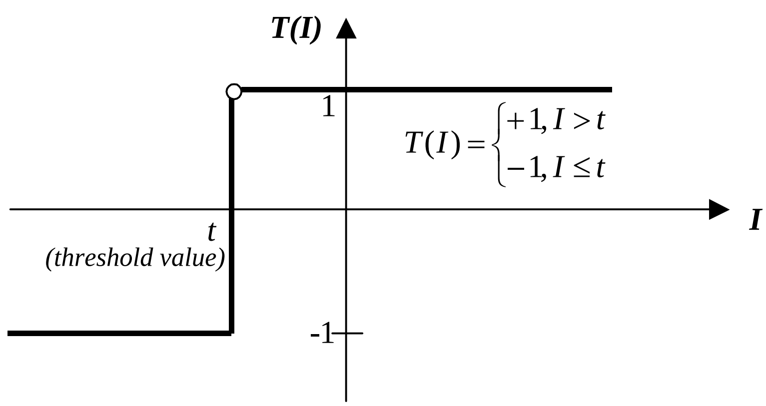


Figure 5.3 Sigmoid Function



(a) A Threshold Function with Values 1 and 0



(b) A Threshold Function with Values 1 and -1

Figure 5.4 Threshold Functions

5.2.1.3 Artificial neural networks

An artificial neural network, which contains several layers, is constituted with a number of artificial neurons. According to Tsoukalas and Uhrig, an artificial neural network can be defined as

> *"A data processing system consisting of a large number of simple, highly interconnected processing elements (artificial neurons) in an architecture inspired by the structure of the cerebral cortex of the brain."*

In practice, three-layered feedforward artificial neural networks are the most utilized multi-layer artificial neural networks. "Feedforward" means no lateral connections exist between the artificial neurons in a given layer and the information flow does not go back to previous layers. Figure 5.5 shows the structure of a simple artificial neural network (Tsoukalas and Uhrig 1997).

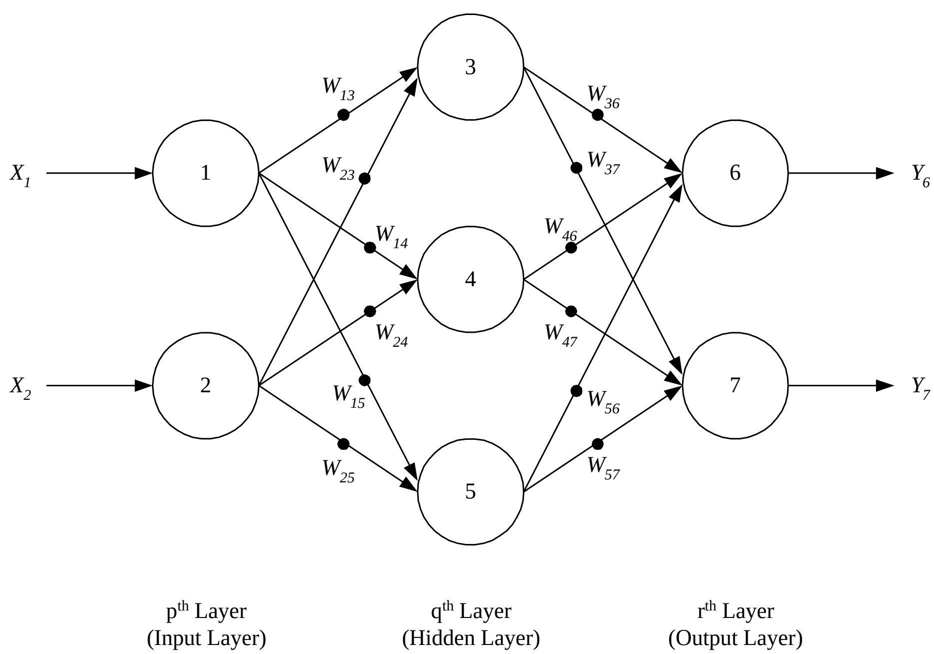


Figure 5.5 Structure of Artificial Neural Network

There are three different layers in the structure of artificial neural networks: the input layer, the hidden layer, and the output layer. The input layer is the incoming layer of the artificial neural network that receives information, and likewise, the output layer is the outgoing layer of the artificial neural network that send out filtered results. The hidden layer is the layer (or the layers) between the input layer and the output layer, which processes (or process) the incoming information based on the stored experience through training.

5.2.1.4 Backpropagation training algorithm

Backpropagation training algorithm is the most frequent method used for the training of multi-layer (three or more) artificial neural networks. It has the following training steps:

1. Assign a small random value to each weight. The value could be positive or negative. The reason of choosing small values is to make the weights adjusted evenly and to avoid the saturating of the artificial neural networks. Also, all the weights should not be equal, because the artificial neural network will not train in some cases.
2. Select an input-output training pair from the training set.
3. Send the input (a number or a vector) to the artificial neural network.
4. Calculate the output value in accordance with the assigned weights and the pre-selected transfer function in each artificial neuron.
5. Compare the calculated output with the target output and compute the error.

6. Adjust the weights so as to minimize the error. (Backpropagation training will be applied for the weight adjustment in the following text.)
7. Repeat steps 2-6 for each input-output training pair until the error for each pair is under a pre-determined acceptance threshold.

Figure 5.6 shows the training process of the backpropagation algorithm. The notation adopted in Figure 5.5 is shown below:

Notation*:*

X_a: The input value of node *a* in the input layer. (*a* = 1 to h)

I^a_b: The input value of node *b* in the a^{th} layer. (For hidden and output layer neurons only); (If *a* = q, *b* = 1 to i ; if *a* = r, *b* = 1 to j)

T^a_b: The output value of node *b* in the a^{th} layer. (For hidden and output layer neurons only); (If *a* = q, *b* = 1 to i ; if *a* = r, *b* = 1 to j)

Y_a: The output value of node *a* in the output layer. (*a* = 1 to j)

W^a_{bc}: The weight on the connection from node *b* in the $(a\text{-}1)^{th}$ layer to node *c* in the a^{th} layer.

t_a: The target value of node *a* in the output layer. (*a* = 1 to j)

ε_a: The difference (or error) between the output and the target on node a in the output layer. (*a* = 1 to j)

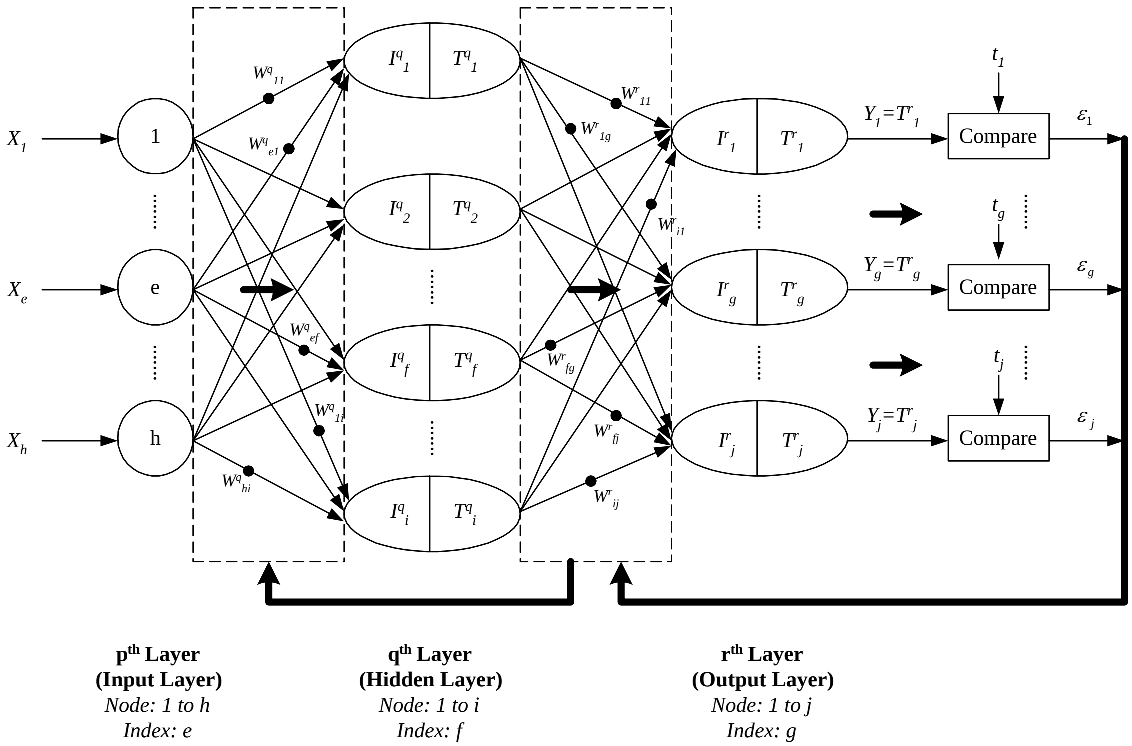


Figure 5.6 Training Process of Backpropagation Algorithm

The backpropagation training algorithm adjusts the weights in a backward manner. The output layer weights will be adjusted first based on the calculated errors, followed by the adjustment of the hidden layer weights. The derivation of the weight change equations for the output and hidden layer weights is listed below (Tsoukalas and Uhrig 1997). In this derivation, a sigmoid transfer function with a scaling constant ϕ and a learning rate α were assumed throughout the network.

Derivation:

The error in the output neuron g can be expressed by

$$\varepsilon_g = t_g - T_g^r \tag{5-2}$$

The weight change equation for the output layer weights is

$$\Delta W_{fg}^{r} = -\alpha \frac{\partial \varepsilon_{g}^{2}}{\partial W_{fg}^{r}} = -\alpha[-2\phi(t_{g} - T_{g}^{r})T_{g}^{r}(1 - T_{g}^{r})T_{f}^{q}] \quad (5\text{-}3)$$

The weight change equation for the hidden layer weights is

$$\Delta W_{ef}^{q} = -\alpha \sum_{g=1}^{j} \frac{\partial \varepsilon_{g}^{2}}{\partial W_{ef}^{q}} = -\alpha[\sum_{g=1}^{j} - 2\phi(t_{g} - T_{g}^{r})T_{g}^{r}(1 - T_{g}^{r})W_{fg}^{r}\phi T_{f}^{q}(1 - T_{f}^{q})X_{e}] \quad (5\text{-}4)$$

The new output layer weights can be calculated as

$$W_{fg}^{r}(new) = W_{fg}^{r}(old) + \Delta W_{fg}^{r} \quad (5\text{-}5)$$

The new hidden layer weights can be calculated as

$$W_{ef}^{q}(new) = W_{ef}^{q}(old) + \Delta W_{ef}^{q} \quad (5\text{-}6)$$

5.2.1.5 Training example

A training example is given in this section to demonstrate the training process of the backpropagation algorithm. Figure 5.7 illustrates a simple three-layer artificial neural network, with given input, target, and weights. In this example, the scaling constant ϕ of the sigmoid transfer function and the learning rate α are assumed to be 1 and 0.5, respectively.

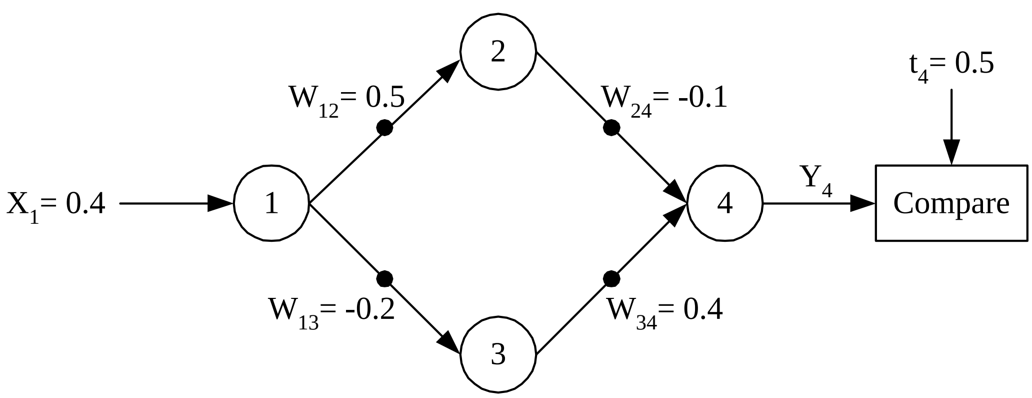


Figure 5.7 Training Example

Solution:

The input and output values of nodes 2, 3 and 4 can be calculated based on Figure 5.2 and Equation 5-1:

$I_2 = X_1 * W_{12} = 0.4 * 0.5 = 0.5$

$T_2 = 1/(1+exp(-0.5)) = 0.5498$

$I_3 = X_1 * W_{13} = 0.4 * (-0.2) = -0.08$

$T_3 = 1/(1+exp(0.08)) = 0.4800$

$I_4 = T_2 * W_{24} + T_3 * W_{34} = 0.5498 * (-0.1) + 0.4800 * 0.4 = 0.1370$

$T_4 = 1/(1+exp(-0.1370)) = 0.5342$

According to Equations 5-3 and 5-4, the weight changes can be computed:

$\Delta W_{24} = -0.5[-2(1)(0.5-0.5342)(0.5342)(1-0.5342)(0.5498)] = -0.0047$

$\Delta W_{34} = -0.5[-2(1)(0.5-0.5342)(0.5342)(1-0.5342)(0.4800)] = -0.0041$

$\Delta W_{12} = -0.5[-2(1)(0.5-0.5342)(0.5342)(1-0.5342)(-0.1)(1)(0.5498)(1-0.5498)(0.4)]$

$= 0.00008$

$\Delta W_{13} = -0.5[-2(1)(0.5-0.5342)(0.5342)(1-0.5342)(0.4)(1)(0.4800)(1-0.4800)(0.4)]$

$= -0.00034$

After the weight changes are available, the new weights can be obtained from Equations 5-5 and 5-6:

$W_{24}(new) = W_{24}(old) + \Delta W_{24} = -0.1 + (-0.0047) = -0.1047$

$W_{34}(new) = W_{34}(old) + \Delta W_{34} = 0.4 + (-0.0041) = 0.3959$

$W_{12}(new) = W_{12}(old) + \Delta W_{12} = 0.5 + 0.00008 = 0.50008$

$W_{13}(new) = W_{13}(old) + \Delta W_{13} = -0.2 + (-0.00034) = -0.20034$

The same calculation procedure can continue until the error is under an accepted threshold value.

5.2.2 Fuzzy logic systems

Fuzzy logic is a theory dealing with relative importance, which coincides with general human intuition. For example, in a hot sunny day, people can feel it is hot, but cannot tell how hot it is in terms of degrees. This is the feature of fuzzy logic systems, which convert linguistic expressions to numerical and analytical forms. The operation of fuzzy logic systems is controlled by a set of If-Then rules. With these rules, fuzzy systems are capable of mapping an input to an appropriate output.

5.2.2.1 Fuzzy sets

Fuzzy sets describe vague concepts, and, unlike crisp sets, do not have clear boundaries. A fuzzy set includes a lot of paired elements, with the form of $(x, \mu_A(x))$. $\mu_A(x)$ denotes the membership of the input number x in the fuzzy set A. Each pair contains an input number x and its membership $\mu_A(x)$, which represents the importance of the input number x and has a value between 0 and 1. A membership function μ maps each input number to its membership value, which is between 0 and 1. Figure 5.8 illustrates a simple membership function. The space of all input numbers is the “universe of discourse,” as the region [0, 20] in Figure 5.8. A fuzzy set A can be expressed as $A=\{(x, \mu_A(x)) \mid x \in X\}$, where X is the universe of discourse (Tsoukalas and Uhrig 1997).

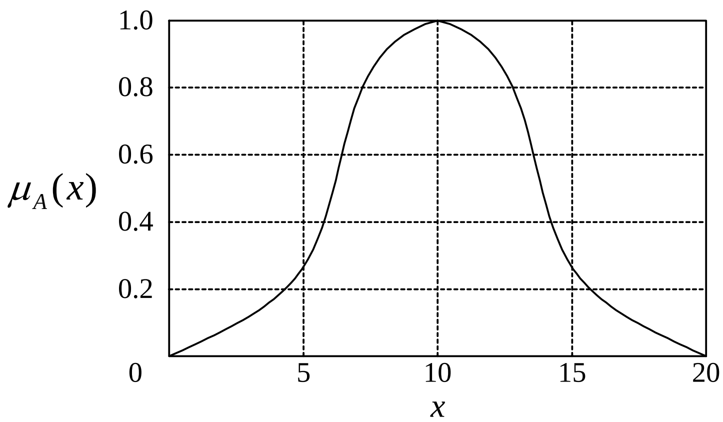


Figure 5.8 Membership Function

5.2.2.2 Fuzzy logical operations

In fuzzy logic systems, the logical operation *"A AND B"* is performed by the *"min(A,B)"* operator. The *"A OR B"* operation is equivalent to the *"max(A,B)"* operation. The *"NOT A"* operation is represented by the *"(1-A)"* operation. Compared with the Boolean logic, the fuzzy logic can be thought of as a superset of the Boolean logic. If the fuzzy logic is performed in its extreme case, only 1 (completely true) or 0 (completely false) are considered, the fuzzy sets can be operated with the standard Boolean logic. However, if partial membership exists in a fuzzy set, the fuzzy logic operation will be required. The *"max"* and *"min"* operators in the fuzzy logic can be represented by the *union symbol* ($\cup$) and the *intersection symbol* ($\cap$), respectively (Tsoukalas and Uhrig 1997). Also, the *"(1-A)"* operation can be represented by the *complement symbol* A^c (Kosko 1992). Table 5.1 shows the comparisons of the Boolean logic and the fuzzy logic operations. Figure 5.9 illustrates the fuzzy logic operations.

Table 5.1 Comparisons of Boolean and Fuzzy Logic Operations

Boolean Logic	**Fuzzy Logic**
A AND B	*min(A,B);* $A \cap B$
A OR B	*max(A,B);* $A \cup B$
NOT A	*(1-A);* A^c

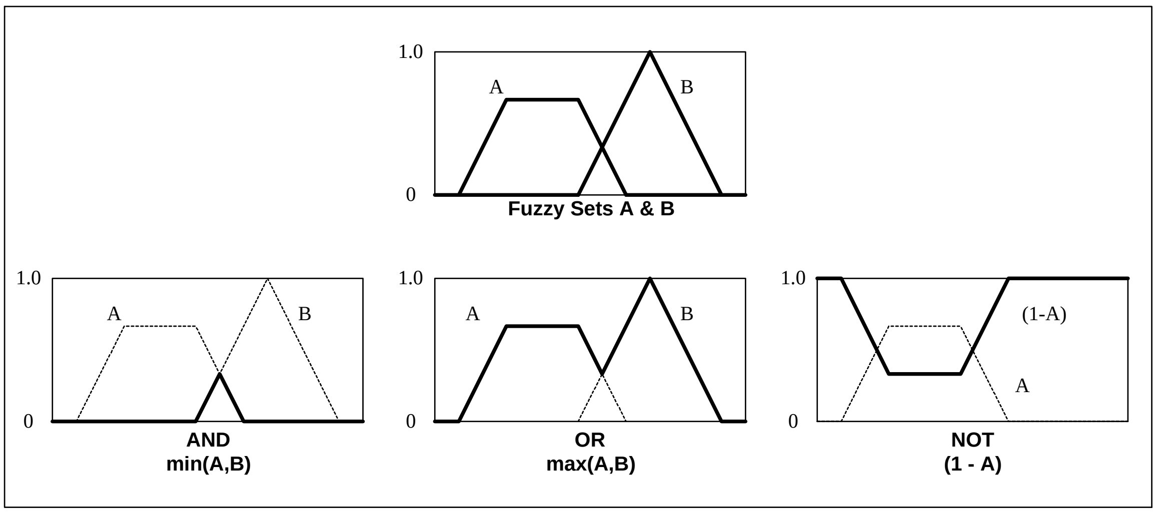


Figure 5.9 Fuzzy Logic Operations

5.2.2.3 Fuzzy inference

Fuzzy inference is a process of converting an input (usually a linguistic description) to an output through fuzzy computation. The Mamdani implication method is the most popular methodology for fuzzy inference systems. The Mamdani implication operator $\phi_{Mamdani}$ can be defined as

$$\phi_{Mamdani}(\mu_A(x), \mu_B(x)) \equiv \mu_A(x) \cap \mu_B(x) \tag{5-7}$$

where the symbol "≡" means "be defined as" (Tsoukalas and Uhrig 1997). In general, fuzzy inference has the following five steps:

1. Input fuzzification
2. Application of fuzzy operations
3. Application of implication method
4. Output aggregation
5. Defuzzification

For a clear illustration, an example is given below to demonstrate the five fuzzy inference steps (The MathWork, Inc. 1999).

Example: Bonus Distribution

A company is going to distribute bonuses to its employees. The fuzzy inference system will be utilized for the bonus distribution. The bonus amount given is based on an employee's "attitude" and the employee's "work done." "Attitude" includes two levels: good and bad. "Work done" has three degrees: much, average, and little. There are three bonus levels: high, medium, and low. The bonus amount ranges from \$100 to \$1000. The If-Then rules adopted for the fuzzy inference system are

Rule 1: If the attitude is good or the work done is much, then the bonus is high.

Rule 2: If the work done is average, then the bonus is medium.

Rule 3: If the attitude is bad or the work done is little, then the bonus is low.

The rating systems for the "attitude" and the "work done" are both from 0 to 10 (i.e., the universe of discourse). Figure 5.10 shows the membership functions of the "attitude", the "work done", and the "bonus." In this case, ratings of 7 and 4 for the "attitude" and the "work done" are assumed for the demonstration of the five fuzzy inference steps.

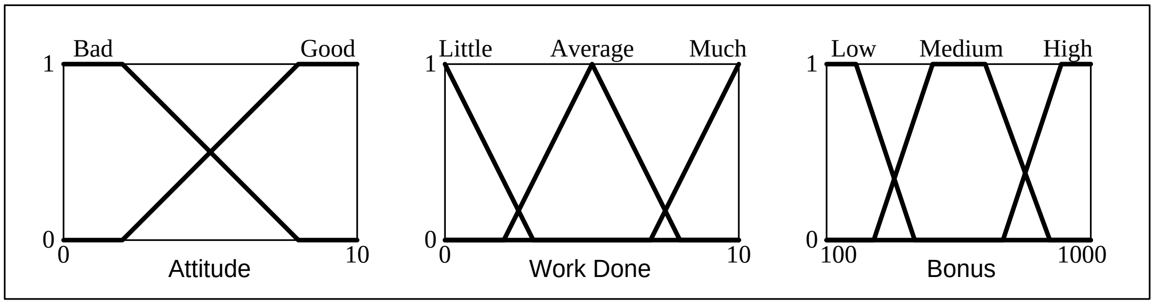


Figure 5.10 Membership Functions of the Fuzzy Inference Example

Step 1: Input fuzzification

The purpose of input fuzzification is to find out the degrees of input variables based on the given input values and the membership functions. In this case, an input value of 7 for the "attitude" means the degree of "the attitude is good" is 0.83, and the degree of "the attitude is bad" is 0.17 (See Figure 5.11). Likewise, a rating of 4 for the "work done" indicates a 0.67 degree for "the work done is average" and a zero degree for both "the work done is much" and "the work done is little." Figure 5.10 depicts the fuzzification of both input variables.

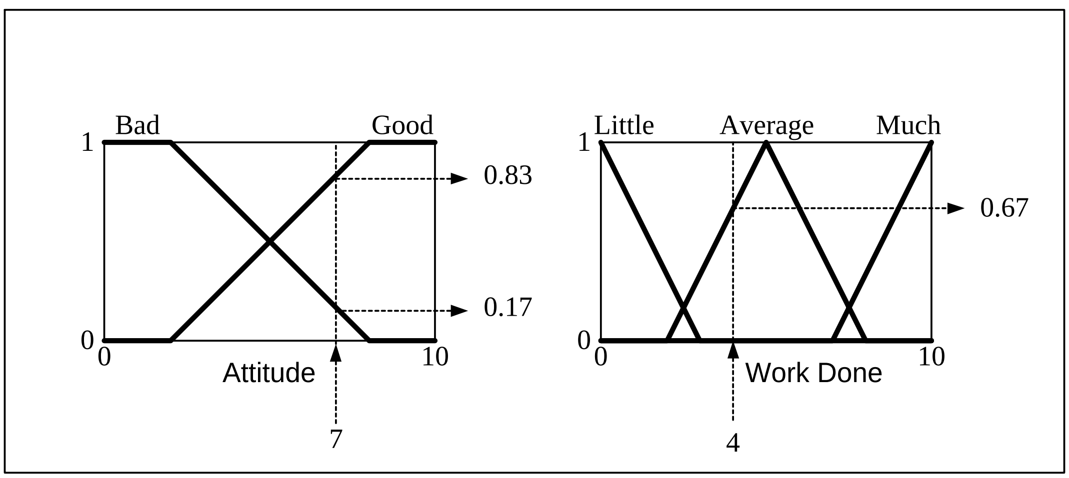


Figure 5.11 Input Fuzzification

Step 2: Application of fuzzy operations

If there are two or more parts in the antecedent of a given fuzzy rule, the fuzzy operations will be applied to get a combined output value. Mostly, the fuzzy operations that will be used are “AND” and “OR.” As described in 5.2.2.2, “AND” and “OR” are calculated using a *min* operator and a *max* operator, respectively, in a fuzzy system. In this case, Rule 1 and Rule 3 both have two parts in their antecedents, and an “OR” operation will be conducted according to the rules. The combined outputs for Rule 1 and Rule 3 are 0.83 and 0.17, respectively. Rule 2 has only one part in its antecedent, whose output value is 0.67 (Figure 5.12).

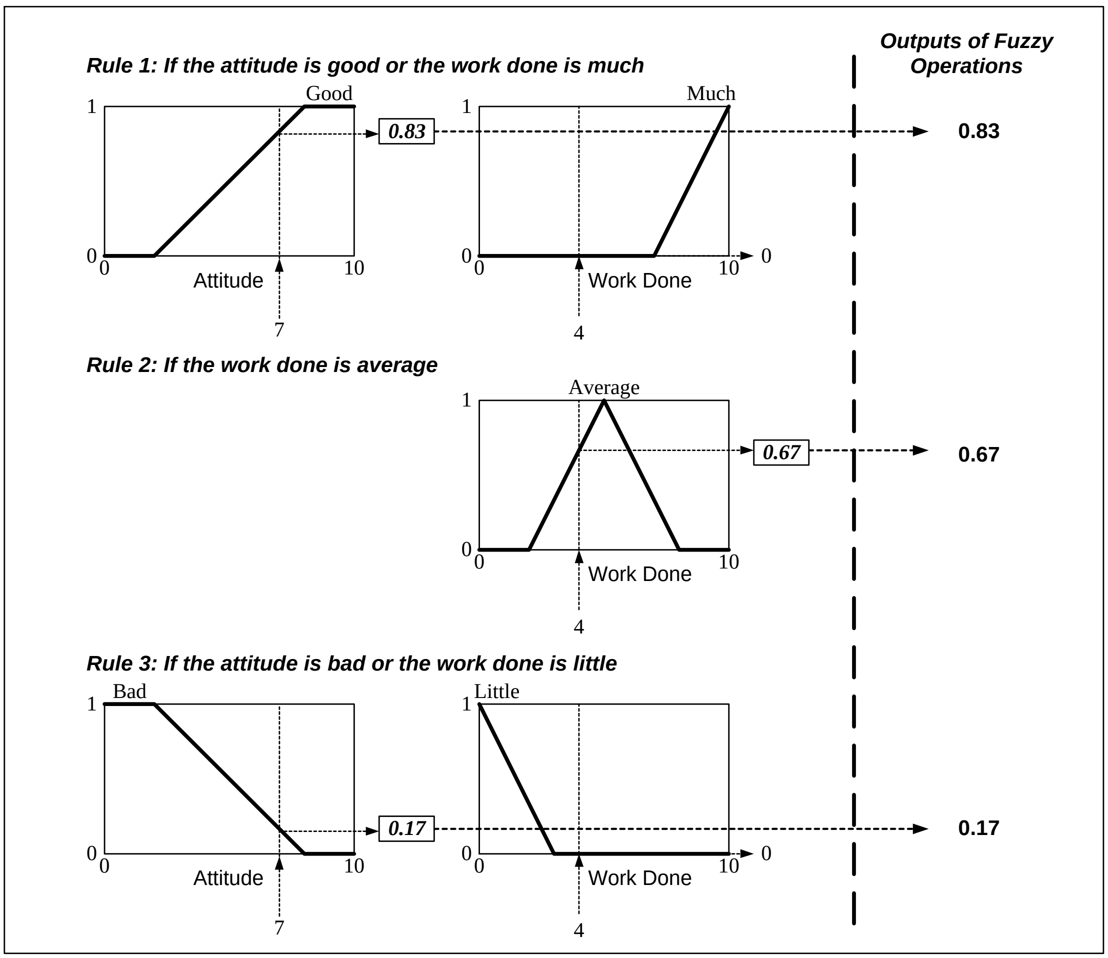


Figure 5.12 Application of Fuzzy Operations

Step 3: Application of implication method

An implication process has a value as its input and a fuzzy set as its output. The input value for an implication process comes from the result of the antecedent of a given fuzzy rule. The output fuzzy set is then reshaped in accordance with the input value and the implication method. In this case, the Mamdani implication method, which truncates the output fuzzy set, is used. Figure 5.13 illustrates the application of the Mamdani implication method to the three given fuzzy rules.

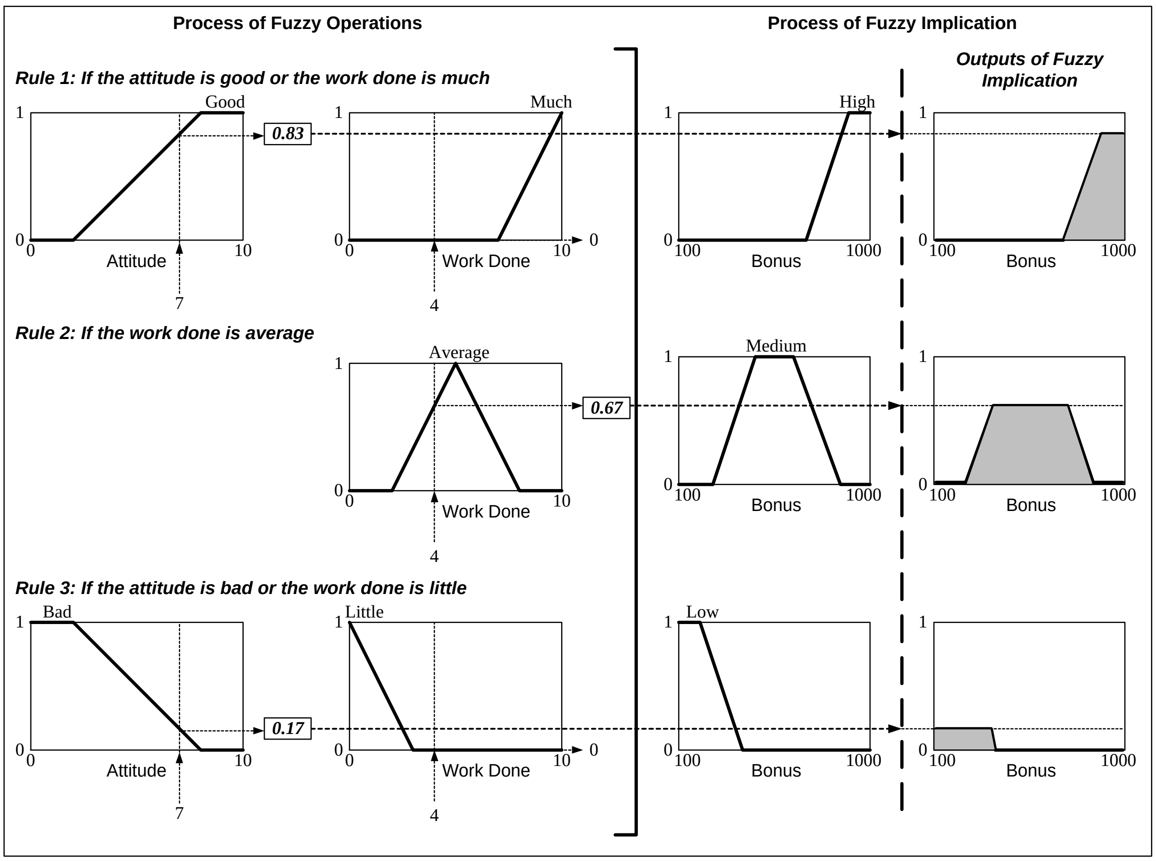


Figure 5.13 Application of Mamdani Implication Method

Step 4: Output aggregation

Several methods are available for the aggregation of the fuzzy implication outputs. Frequently used methods include the “max” method and the “sum” method. The “max” method aggregates each fuzzy implication output by taking the maximum value for each point in the universe of discourse. The “sum” method aggregates by summing all fuzzy implication outputs. The “max” method is adopted in this case. Figure 5.14 illustrates the aggregation of the fuzzy implication outputs.

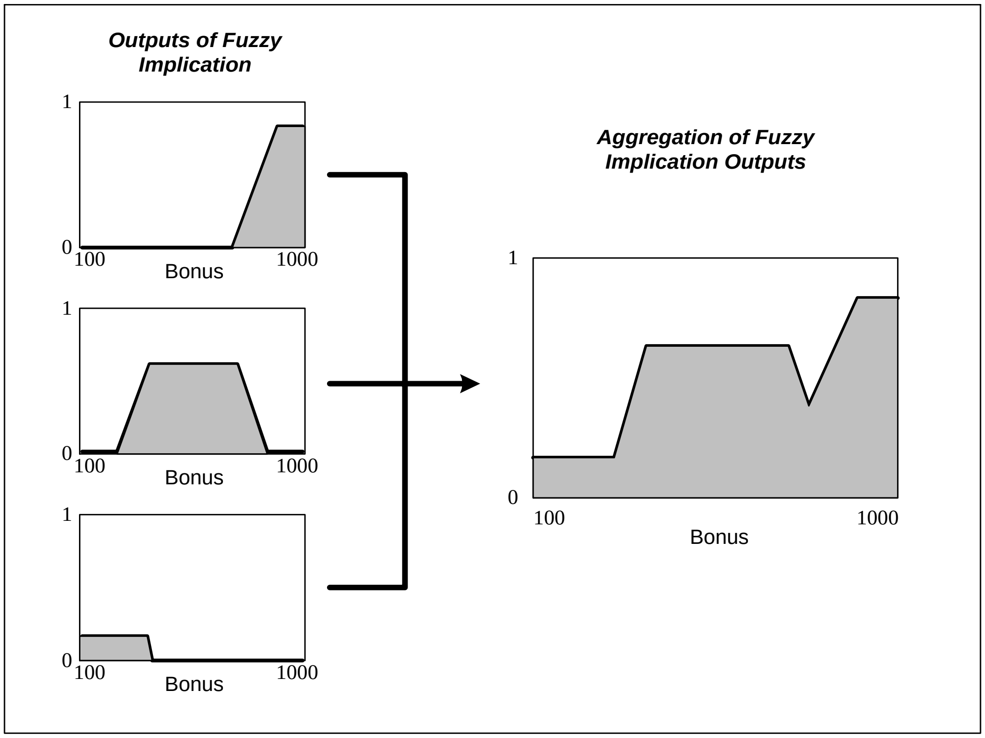


Figure 5.14 Aggregation of Fuzzy Implication Outputs

Step 5: Defuzzification

Defuzzification, which is the last step in the fuzzy inference process, converts the aggregated implication output to a single value. There are several defuzzification methods available, such as the centroid method (or the center of area method), the bisector method, the mean of maxima method, the center of sums method, and so forth. The most common one is the centroid method (or the center of area method), which returns the center of area under the aggregated curve. The centroid defuzzification method is utilized in this example. After the defuzzification process, an output value of \$611, which is the bonus to be given in this case, can be obtained (Figure 5.15).

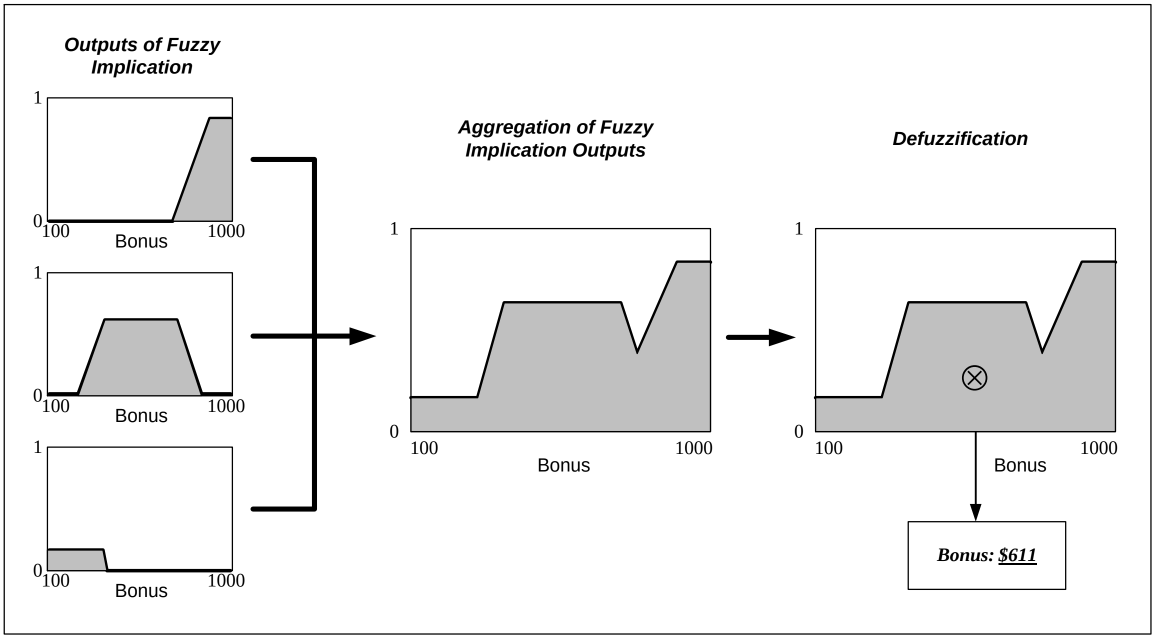


Figure 5.15 Defuzzification

5.2.3 K-means algorithm for pattern recognition

The K-means algorithm, which divides a group of samples based on the distance to the cluster means, is the simplest clustering method. To apply the K-means algorithm, the feature vector of each sample and the number of clusters should be determined in advance. Also, the number of clusters should be no more than the number of samples. In general, the K-means algorithm has the following steps:

1. Randomly assign K samples' feature vectors as the first K means ($M^{(1)}_i$, $i = 1$ to K, and $^{(1)}$ indicates the first iteration) of clusters.
2. Assign the remaining $(N - K)$ samples to the closest clusters based on the distance between each sample and each cluster mean, where N is the total number of samples.
3. Re-compute the mean of each new cluster ($M^{(2)}_i$, $i = 1$ to K, and $^{(2)}$ indicates the second iteration).

4. Reassign the *N* samples to the clusters with the closest means.

5. Repeat 3 – 4 until no further change occurs.

The following example demonstrates the flow of the K-means algorithm.

Example: Spot Discrimination

The purpose of this example is to discriminate the spotted areas from the background. A spotted grayscale image will be use for spot discrimination in this example. Each pixel in a grayscale image could have a gray level value between 0 and 255. A 0 gray level value indicates 100% black, and a 255 gray level value means 100% white. Figure 5.16 illustrates a spotted grayscale image.

		Y 1	2	3
	1	86	30	60
X	2	110	50	95
	3	100	72	150

Figure 5.16 Spotted Grayscale Image

This example is a one-dimensional problem, because the only concerns are the gray level values of the nine pixels. Thus, each pixel has a feature value (i.e. the gray level value), instead of a feature vector. The nine pixels will be divided into two groups: the spot and the background. The spotted areas are darker and will be assigned 1 values after the spot discrimination is done. The background is lighter and will be given 0 values. Therefore, after the spot discrimination is done, the original grayscale image will become a binarized image, with 1's representing the spots and 0's representing the background. The gray level value of each pixel can be denoted as *G(X,Y)*, which indicates the gray level value of the pixel located on *(X,Y)*. For instance, *G(1,1)* = 86 and *G(2,3)* =

95. Now the K-means algorithm will be performed following the aforementioned five steps:

Step 1: Assign $G(1,1) = M^{(1)}_1$ = 86 and $G(1,2) = M^{(1)}_2$ = 30.

Step 2: Assign the remaining 7 samples to the two clusters. For $G(1,3)$,

Distance between $G(1,3)$ and $M^{(1)}_1$: $d(G(1,3), M^{(1)}_1) = | 60 - 86 | = 26$

Distance between $G(1,3)$ and $M^{(1)}_2$: $d(G(1,3), M^{(1)}_2) = | 60 - 30 | = 30$

Therefore, $G(1,3)$ is assigned to Cluster 1.

The same method can be performed on the other 6 samples. The summarized clustering information is as follows:

Cluster 1: {$G(1,1), G(1,3), G(2,1), G(2,3), G(3,1), G(3,2), G(3,3)$}

Cluster 2: {$G(1,2), G(2,2)$}

Step 3: Re-computer the means for both clusters.

$M^{(2)}_1 = (86 + 60 + 110 + 95 + 100 +72 +150) / 7 = 96$

$M^{(2)}_2 = (30 + 50) / 2 = 40$

Step 4: Reassign the 9 samples to the two clusters. The summarized information is shown below:

Cluster 1: {$G(1,1), G(2,1), G(2,3), G(3,1), G(3,2), G(3,3)$}

Cluster 2: {$G(1,2), G(1,3), G(2,2)$}

Step 5: Repeat Steps 3 – 4 until no further change occurs. The summarized information is shown below:

$M^{(3)}_1 = (86 + 110 + 95 + 100 +72 +150) / 6 = 102$

$M^{(3)}_2 = (30 + 60 + 50) / 3 = 46.7 \approx 47$

Cluster 1: {*G(1,1), G(2,1), G(2,3), G(3,1), G(3,3)*}

Cluster 2: {*G(1,2), G(1,3), G(2,2), G(3,2)*}

$M^{(4)}{}_1$ = (86 + 110 + 95 + 100 +150) / 5 = 108.2 ≈ 108

$M^{(4)}{}_2$ = (30 + 60 + 50 + 72) / 4 = 53

Cluster 1: {*G(1,1), G(2,1), G(2,3), G(3,1), G(3,3)*}

Cluster 2: {*G(1,2), G(1,3), G(2,2), G(3,2)*}

No further change in clustering occurs, and the clustering with the K-means algorithm is done.

After the clustering is completed, all the pixels in Cluster 1 will be assigned 0 values as the background. All the pixels in Cluster 2 will be assigned 1 values as the spots. The binarized spotted image is shown in Figure 5.17. The summarized data of this example are shown in Table 5.2.

		Y		
		1	2	3
	1	0	1	1
X	2	0	1	0
	3	0	1	0

Figure 5.17 Binarized Spotted Image

Table 5.2 Summary of Spot Discrimination Example

	$M^{(1)}_1$ = 86 and $M^{(1)}_2$ = 30		Cluster Assignment	
	Distance to $M^{(1)}_1$	Distance to $M^{(1)}_2$	Cluster 1	Cluster 2
$G(1,1)$ = 86	0	56	x	
$G(1,2)$ = 30	56	0		x
$G(1,3)$ = 60	26	30	x	
$G(2,1)$ = 110	24	80	x	
$G(2,2)$ = 50	36	20		x
$G(2,3)$ = 95	9	65	x	
$G(3,1)$ = 100	14	70	x	
$G(3,2)$ = 72	14	42	x	
$G(3,3)$ = 150	64	120	x	
	$M^{(2)}_1$ = 96 and $M^{(2)}_2$ = 40		**Cluster Assignment**	
	Distance to $M^{(2)}_1$	Distance to $M^{(2)}_2$	Cluster 1	Cluster 2
$G(1,1)$ = 86	10	46	x	
$G(1,2)$ = 30	66	10		x
$G(1,3)$ = 60	36	20		x
$G(2,1)$ = 110	14	70	x	
$G(2,2)$ = 50	46	10		x
$G(2,3)$ = 95	1	55	x	
$G(3,1)$ = 100	4	60	x	
$G(3,2)$ = 72	24	32	x	
$G(3,3)$ = 150	54	110	x	
	$M^{(3)}_1$ = 102 and $M^{(3)}_2$ = 47		**Cluster Assignment**	
	Distance to $M^{(3)}_1$	Distance to $M^{(3)}_2$	Cluster 1	Cluster 2
$G(1,1)$ = 86	16	39	x	
$G(1,2)$ = 30	72	17		x
$G(1,3)$ = 60	42	13		x
$G(2,1)$ = 110	8	63	x	
$G(2,2)$ = 50	52	3		x
$G(2,3)$ = 95	7	48	x	
$G(3,1)$ = 100	2	53	x	
$G(3,2)$ = 72	30	25		x
$G(3,3)$ = 150	48	103	x	
	$M^{(4)}_1$ = 108 and $M^{(4)}_2$ = 53		**Cluster Assignment**	
	Distance to $M^{(4)}_1$	Distance to $M^{(4)}_2$	Cluster 1	Cluster 2
$G(1,1)$ = 86	22	33	x	
$G(1,2)$ = 30	78	23		x
$G(1,3)$ = 60	48	7		x
$G(2,1)$ = 110	2	57	x	
$G(2,2)$ = 50	58	3		x
$G(2,3)$ = 95	13	42	x	
$G(3,1)$ = 100	8	47	x	
$G(3,2)$ = 72	36	19		x
$G(3,3)$ = 150	42	97	x	

5.2.4 Image thresholding

Image thresholding, which is usually applied to grayscale images, is another method used for image segmentation. The concept of image thresholding is very simple. First, select an appropriate threshold value. Then, use the threshold value to segment an image. Pixels with gray level values larger than the threshold value are considered as the background, and pixels with gray level values smaller than the threshold value are thought of as the object (or the foreground), or vice versa. Pixels with the same value as the threshold can be classified as either the object or the background. Image thresholding can be expressed by Equation 5-8:

$$F(x,y)=\begin{cases}P_B\,, G(x,y)\geq t\\ P_O\,, G(x,y)<t\end{cases} \tag{5-8}$$

where *G(x,y)* is the gray level function, which maps the pixel located on *(x,y)* to its corresponding gray level value. *t* is the threshold value. *F(x,y)* is the thresholding function that classifies pixels as the background pixels (P_B) or the object pixels (P_o). Image thresholding can also divide an image into *N* segments. In this case, *(N-1)* threshold values are needed as shown in Equation 5-9 (AbdelRazig 1999).

$$F(x,y)=\begin{cases}P_1\ , & G(x,y)\geq\ t_1\\ P_2\ , & t_1>G(x,y)\geq\ t_2\\ & \vdots\\ P_N\ , & t_{N-1}>G(x,y)\end{cases} \tag{5-9}$$

The criterion for image thresholding is to minimize the misclassification errors. There are two types of misclassification errors: the background error and the object error. The background error is referred to as the error that the background pixels are misclassified as object pixels. Likewise, the object error is referred to the error that the object pixels are misclassified as the background pixels. The schematic representations of the background error and the object error are shown in Figure 5.18 and Figure 5.19, respectively. The appropriate threshold value that brings the minimum combined error (including both the background error and the object error) can be obtained by means of statistical methods. Generally, for a bimodal histogram as shown in Figure 5.18 or Figure 5.19, the optimal threshold value falls on the valley of the histogram.

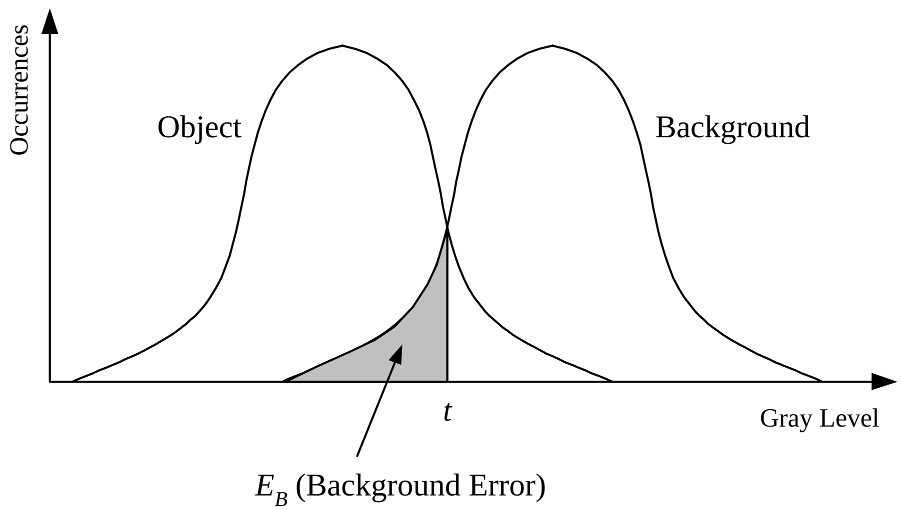


Figure 5.18 The Background Error

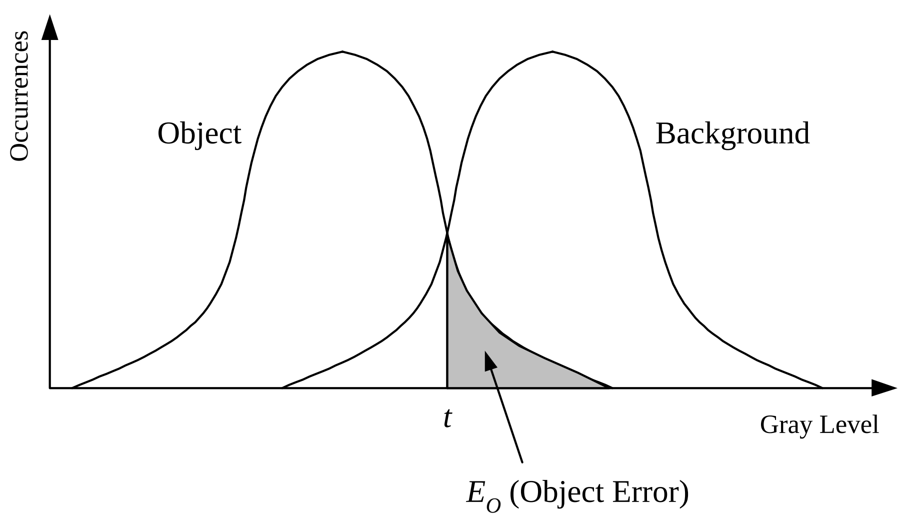


Figure 5.19 The Object Error

5.3 Methodology of Neuro-Fuzzy Recognition Approach

The neuro-fuzzy recognition approach (NFRA) conducts an area-based image processing. Figure 5.20 illustrates the methodology and processing flow of this approach.

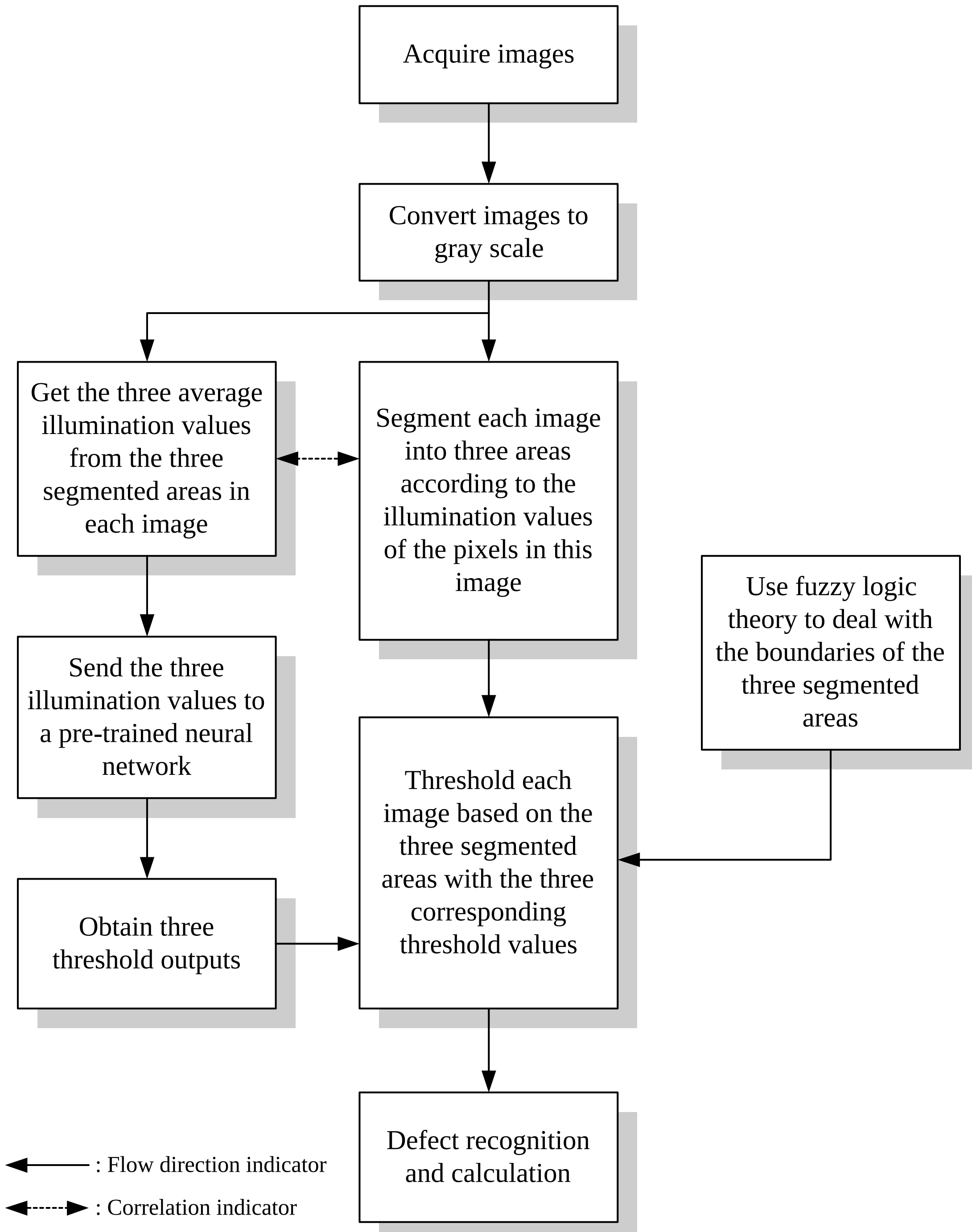


Figure 5.20 Methodology of Neuro-Fuzzy Recognition Approach (NFRA)

First, the acquired image should be converted to gray scale. The obtained grayscale image will then be sent to an image processing software for illumination-based segmentation. The segmentation divides an image into three areas in accordance with the illumination of the pixels in the image. The three average illumination values of the three areas will be collected and input to a pre-trained artificial neural network. The output of the artificial neural network will be three threshold values, which will be used for area-based image thresholding later. Meanwhile, the fuzzy logic theory will be applied to the segmented grayscale image and adjust the gray level values of the cells on both sides of the boundaries. After the three threshold values are available and the boundaries between areas are processed with the fuzzy logic system, the segmented grayscale image will be thresholded with the three obtained threshold values and the defects can be recognized and calculated.

5.4 Training of Artificial Neural Network

The artificial neural network plays an important role in the neuro-fuzzy recognition approach (NFRA). It automatically generates three optimal threshold values for later image thresholding. In this section, the rationale of how the artificial neural network is trained and how to obtain the required training pairs (an input and a target output is called a training pair) is presented.

In the training of the artificial neural network, the following assumption is made: The defect (or object) discrimination results using the K-means algorithm are assumed to be accurate and will serve as the targets which will be compared with the outputs from the artificial neural network.

Figure 5.21 shows the training process of the artificial neural network. To begin with, a sample grayscale image should be segmented into three areas based on illumination using an appropriate image processing software. The three average illumination values of the three areas will be the input to the artificial neural network.

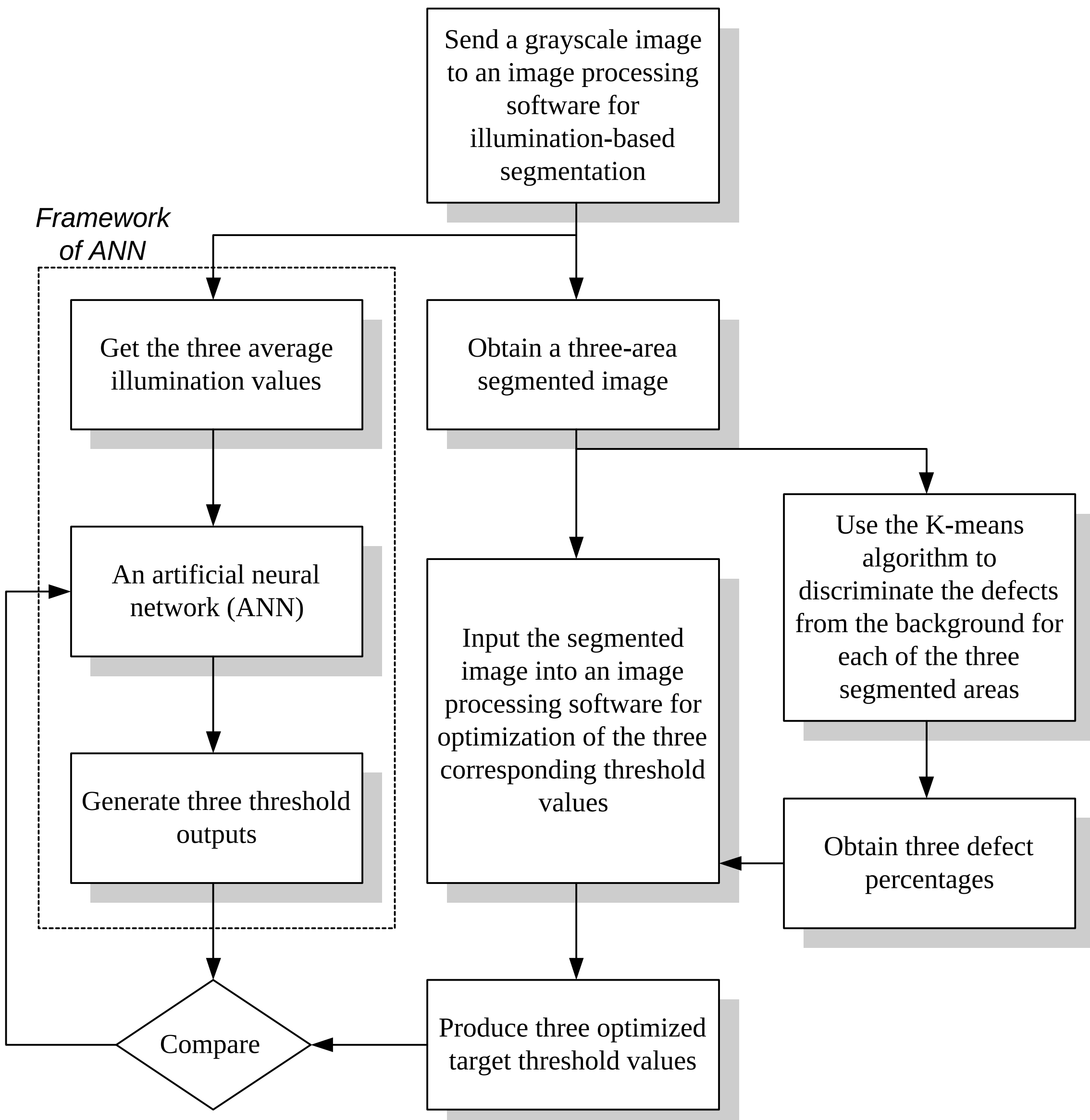


Figure 5.21 Training Process of Artificial Neural Network

Then, the K-means algorithm will be applied to the segmented image and discriminate the defects (or the objects) from the background for each area. The defect (or object) percentage of each area will be computed. Based on the three defect percentages, the optimal threshold values for the three-segmented areas can be acquired by means of an image processing software. The three optimal threshold values are the target values to the artificial neural network and will be compared with the three threshold outputs for further training until the error is acceptably small.

5.5 Procedures of Fuzzy Adjustment

The fuzzy adjustment ought to be applied to the image cells on both sides of the boundaries between areas, as Figure 5.22 indicates. Figure 5.23 illustrates the schematic representation of the fuzzy adjustment. Two inputs are included in this fuzzy system, the “positive difference” and the “negative difference.” The output is the “gray level adjustment.” A set of nine If-Then rules constitutes the kernel of the fuzzy system.

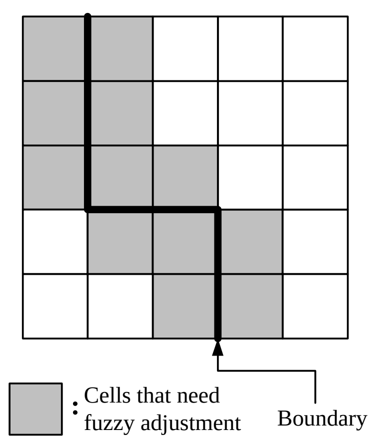


Figure 5.22 Cells That Need Fuzzy Adjustment

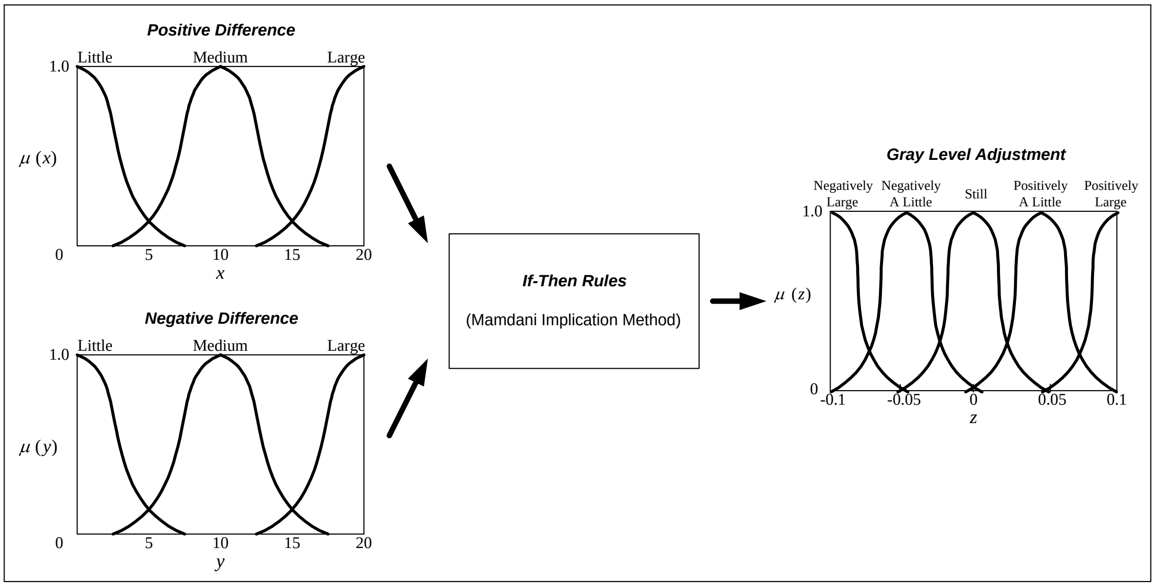


Figure 5.23 Schematic Representation of Fuzzy Adjustment

For a clear presentation, the fuzzy adjustment system will be broken into three parts, the inputs, the If-Then rules, and the output, for explanation.

The Inputs

Gray level values are the concerns of the fuzzy adjustment. Both the inputs "positive difference" and "negative difference" have three levels: large, medium, and little. The universe of discourse for both inputs ranges from 0 to 20. Differences (both positive and negative) larger than 20 are counted as 20. For an ordinary cell that needs fuzzy adjustment and is located on *(x,y)*, four neighboring cells, *(x+1,y)*, *(x-1,y)*, *(x,y+1)*, and *(x,y-1)*, need be considered for difference calculation. In this case, each of the four neighboring cells has a weight of 1/4 (See Figure 5.24(a)). For an edge cell, only three neighboring cells are considered for difference calculation, and each of them is assigned a weight of 1/3 (See Figure 5.24(b)). Likewise, for a corner cell, only two neighboring cells are considered and each of them has a weight of 1/2 (Figure 5.24(c)).

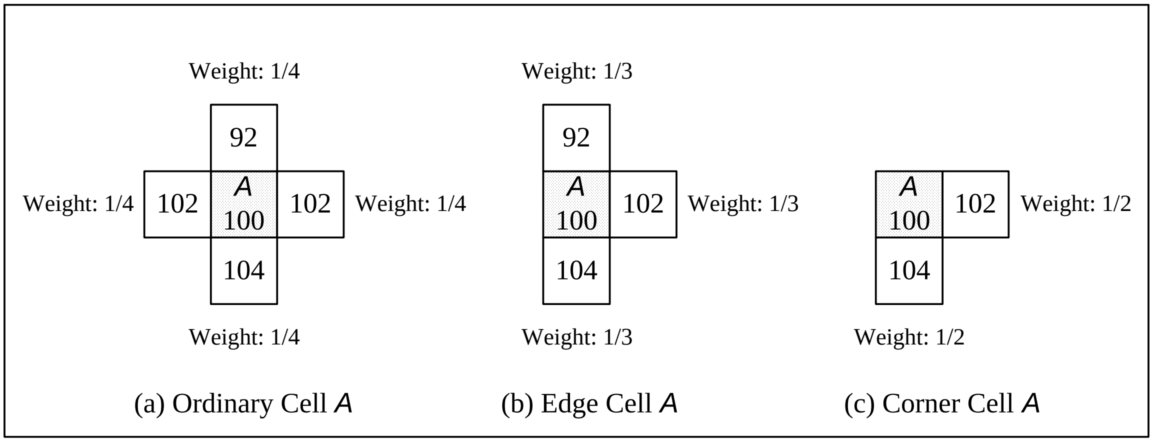


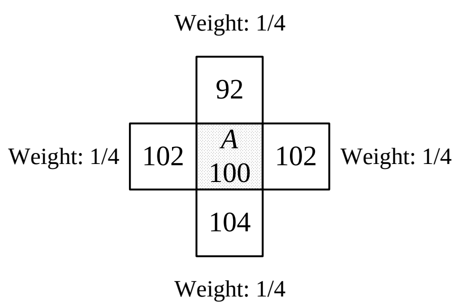
Figure 5.24 Weighting of Different Cell Types

The concept of the difference calculation is pretty simple. For an image cell *A*, those neighboring cells whose gray level values are larger than the gray level value of cell *A* are components of the positive difference calculation. Those neighboring cells with gray level values smaller than the gray level value of cell *A* are included in the negative difference calculation. The difference calculation starts with the computation of the gray level difference between cell *A* and its neighboring cells, followed by the multiplication of each gray level difference and its corresponding weight. Finally, all results after multiplication are summed as the gross difference. The calculation of the positive difference and the negative difference should be conducted separately. Equations 5-10 and 5-11 formulate the calculation of the positive difference and the negative difference, respectively, where $G(x_i,y_i)$ indicates the gray level value of the neighboring pixel (x_i,y_i) of (x,y) and W indicates the corresponding weight of (x_i,y_i). (x_i,y_i) can be $(x+1,y)$, $(x-1,y)$, $(x,y+1)$, or $(x,y-1)$. The m in Equation 5-10 means the number of neighboring pixels with gray level values larger than that of the pixel to be adjusted. The n in Equation 5-11 is referred to the number of neighboring pixels with gray level values smaller than that of the pixel to be adjusted. The sum of m and n should be equal to N, the total number of neighboring pixels, as shown in Equation 5-12. Figure 5.25 illustrates the calculation of both positive and negative gray level differences.

$$Diff_P = \begin{cases} 0 & , m = 0 \\ \sum_{i=1}^{m} \left| G(x_i, y_i) - G(x, y) \right| \times W & , m \geq 1 \end{cases} \tag{5-10}$$

$$Diff_N = \begin{cases} 0 & , n = 0 \\ \sum_{i=1}^{n} \left| G(x_i, y_i) - G(x, y) \right| \times W & , n \geq 1 \end{cases} \tag{5-11}$$

$$N = m + n \tag{5-12}$$



Positive Difference *= (1/4)(102-100) + (1/4)(102-100) + (1/4)(104-100) = 2*

Negative Difference *= (1/4)(100-92) = 2*

Figure 5.25 Gray Level Difference Calculation

The Output

The “gray level adjustment” is the output of the fuzzy system, which contains five different levels: negatively large, negatively a little, still, positively a little, and positively large. The output of the “gray level adjustment” ranges from –0.1 to 0.1. This means that, in the extreme cases, the gray level value of a cell to be adjusted could be increased or decreased up to 10%. The effective output range depends on the membership functions selected for the inputs and the output. The adjusted gray level value can be expressed by the following equation:

$$G_{new}(x, y) = G_{old}(x, y) * (1 + \beta) \tag{5-13}$$

where $G_{new}(x,y)$ and $G_{old}(x,y)$ represent the new gray level value and the old gray level value of the cell located on (x,y), respectively. β is the gray level adjustment amount, which is the output of the fuzzy adjustment system.

The If-Then Rules

There are nine If-Then rules involved in this fuzzy adjustment system. They are listed in Table 5.3. The Mamdani implication method is used in this system.

Table 5.3 If-Then Rules for Fuzzy Adjustment

IF	Positive Difference	AND	Negative Difference	THEN	Gray Level Adjustment
IF	**Large**	AND	**Large**	THEN	**Still**
	Large		*Medium*		*Positively A Little*
	Large		*Little*		*Positively Large*
	Medium		*Large*		*Negatively A Little*
	Medium		*Medium*		*Still*
	Medium		*Little*		*Positively A Little*
	Little		*Large*		*Negatively Large*
	Little		*Medium*		*Negatively A Little*
	Little		*Little*		*Still*

5.6 Stepwise Neuro-Fuzzy Recognition Model

The stepwise neuro-fuzzy recognition model was evolved from the methodology of the neuro-fuzzy recognition approach (NFRA). Therefore, they are basically similar. The purpose of the stepwise neuro-fuzzy recognition model is to demonstrate the detailed procedures of how to implement the neuro-fuzzy recognition approach (NFRA) in practice. The model contains seven steps, from image acquisition to defect recognition and calculation. Each step will be described in detail in the following text. Also, figures were used to provide a clear picture. Figure 5.26 illustrates the backbone of the stepwise neuro-fuzzy recognition model.

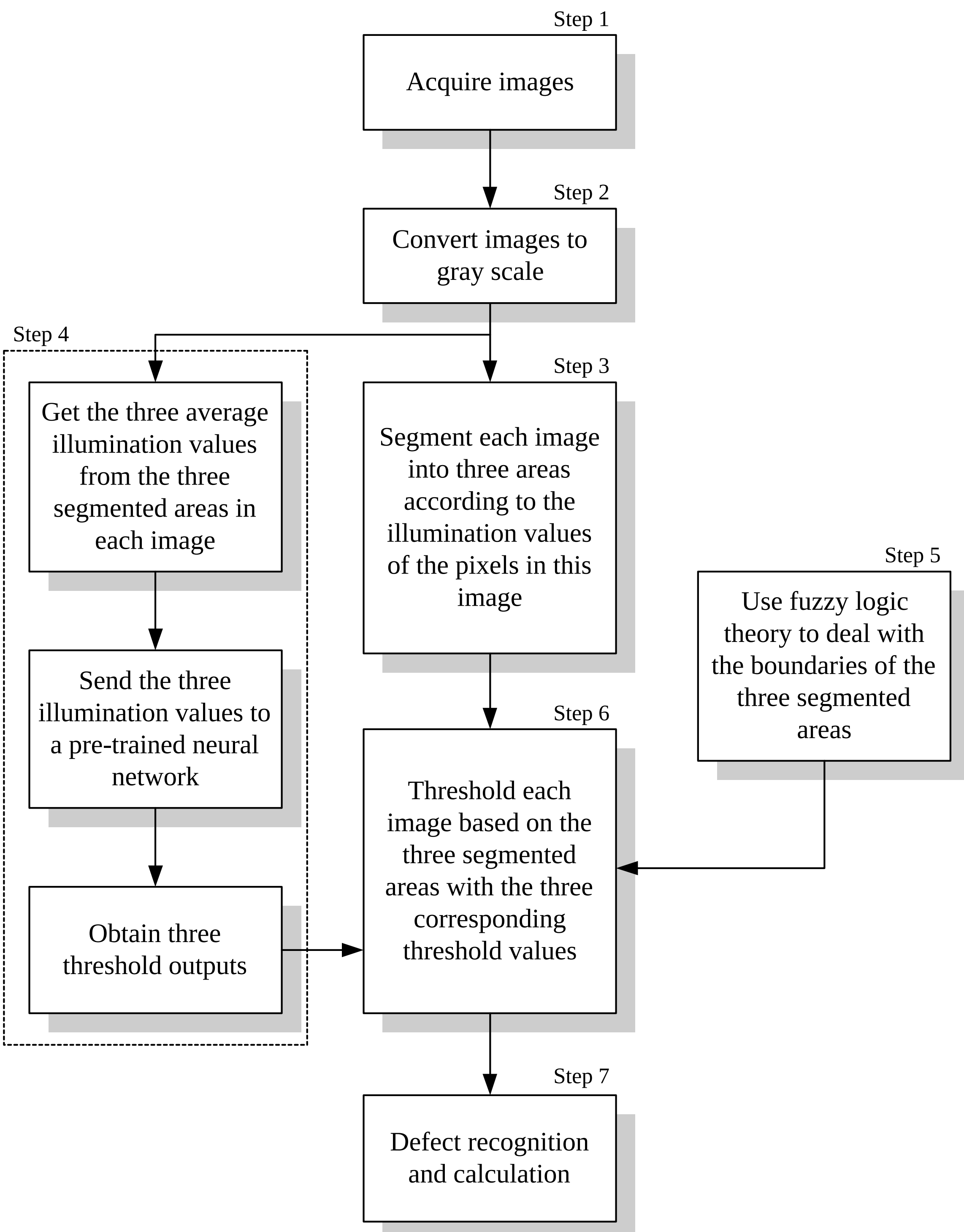


Figure 5.26 Stepwise Neuro-Fuzzy Recognition Model

Step 1:

Image acquisition is the first step of the neuro-fuzzy recognition model. Image data can be acquired by using a digital camera, and then be transferred to a computer. Figure 5.27 depicts the image acquisition process.

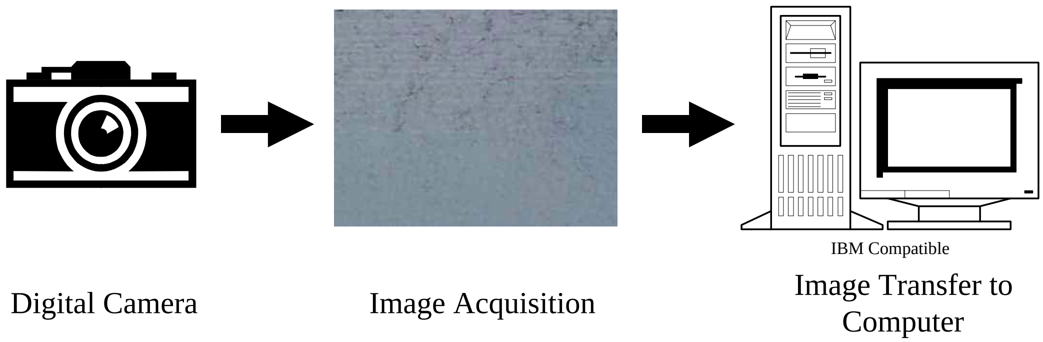


Figure 5.27 Image Acquisition

Step 2:

The second step is to convert the image to gray scale using an image processing software. In order to process an image in an efficient and effective way, the image is usually converted to gray scale before processing. Figure 5.28 demonstrates the process of image conversion to gray scale.

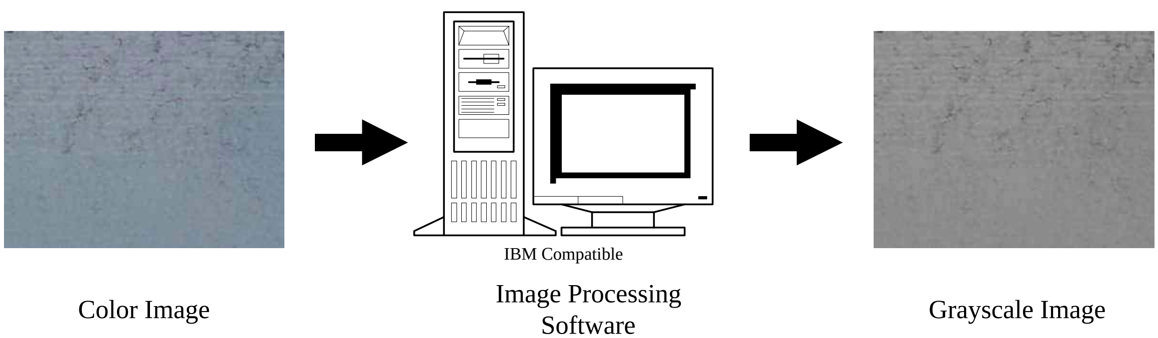


Figure 5.28 Image Conversion to Gray Scale

Step 3:

After converting the image to gray scale, the illumination value of each pixel can be found by utilizing an appropriate image processing software. All the pixels in the image are then separated into three groups in accordance with their illumination values. Illumination values have values between 0 and 1. 0 indicates the darkest and 1 indicates and brightest. The original image now becomes a three-area segmented image. The average illumination values of the three areas will be computed and serve as the input to a pre-trained artificial neural network. The image thresholding performed later is based on the three-segmented areas. Figure 5.29 illustrates the illumination-based image segmentation.

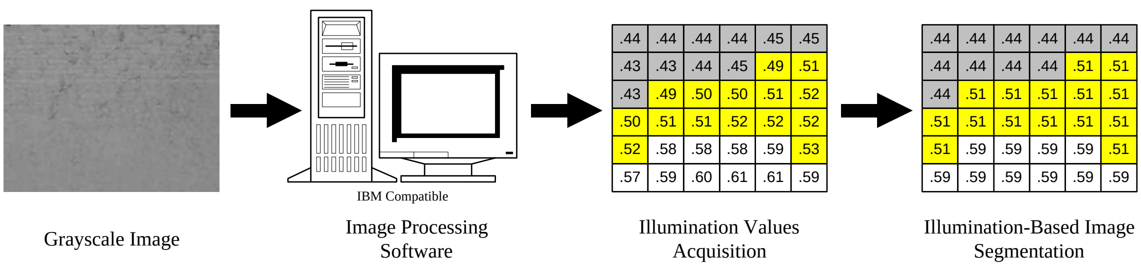


Figure 5.29 Illumination-Based Image Segmentation

Step 4:

Once the image segmentation is completed, the three average illumination values of the three areas will be sent to a pre-trained neural network to generate three corresponding threshold values, which range from 0 to 255. The calculation of this part may be tracked back to using the equations shown in Figure 5.2. Outputs of all the neurons in the input layer should be computed and forwarded to the hidden layer(s). Similarly, the outputs from the hidden layer will be sent to the output layer and produce the three threshold values. Demonstration of this process can be seen from the training example in 5.2.1.5. The training set for the artificial neural network should be diverse so that the trained artificial neural network will be well rounded and fault tolerant. Figure 5.30 illustrates the neural computing process of the three threshold values.

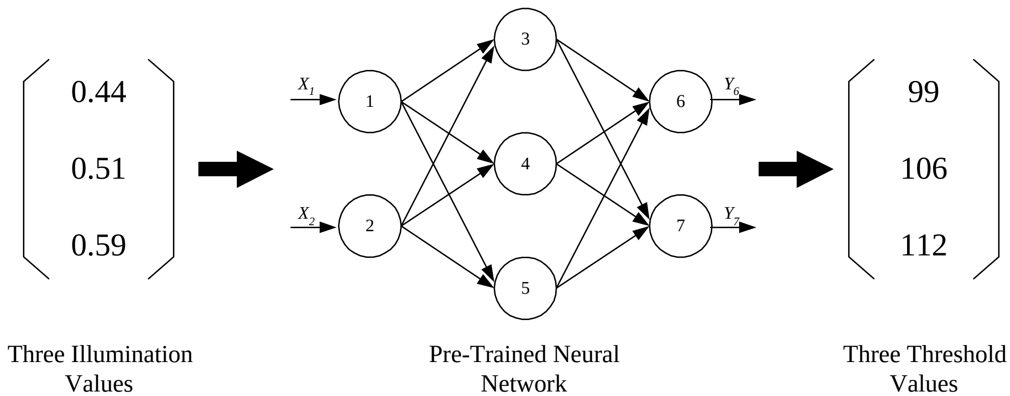


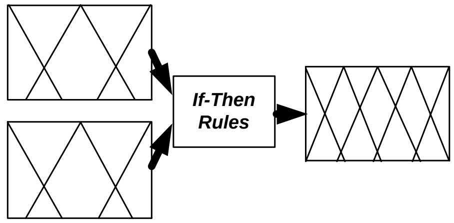
Figure 5.30 Neural Computing of Threshold Values

Step 5:

In this step, the fuzzy adjustment system is utilized to adjust the gray level values of the image cells along the boundaries. The gray level adjustment range is from –10% to +10%. Figure 5.31 shows the flow of fuzzy adjustment. An example of the fuzzy adjustment can be seen from the bottom left pixel of the original grayscale image. This pixel has gray level value 115, with positive difference value 0 (115-115=0) and negative difference value 5 (115-110=5). The positive and negative values will then be sent to the fuzzy adjustment system. Based on the If-Then rules shown in Table 5.3, suppose that the output of the fuzzy adjustment system is -0.008. (The fuzzy inference process can be seen from the bonus distribution example in 5.2.2.3.) Using Equation 5-13, the adjusted gray level value of the bottom left pixel is 114 (115*(1-0.008)=114).

97	101	101	102	103	103
101	101	98	98	109	109
102	109	103	104	108	109
109	110	110	111	111	105
110	114	114	114	114	112
115	115	111	110	115	115

Original Grayscale Image



Fuzzy Adjustment System

97	101	101	102	104	103
101	101	98	98	108	109
102	110	104	105	108	109
108	110	110	111	111	105
110	114	113	114	114	112
114	115	111	110	115	115

Grayscale Image After Fuzzy Adjustment

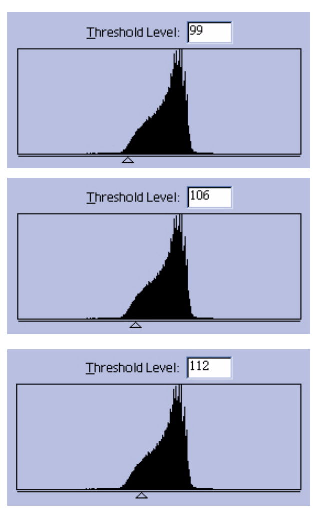
Figure 5.31 Fuzzy Adjustment on Boundary Cells

Step 6:

After the three threshold values are obtained and the fuzzy adjustment is made, each area can be thresholded according to its corresponding threshold value. Pixels with gray level values smaller than the threshold values (i.e., darker) are considered as the defects (or rusts in this case), and pixels with gray level values larger than the threshold values (i.e., brighter) are considered as the background. Figure 5.32 depicts the illumination-based thresholding process. In Figure 5.32, the values in the grayscale image represent the gray level values of pixels. The thresholded image is a binary image, with 0's representing the background and 1's representing the defects (rusts).

97	101	101	102	104	103
101	101	98	98	108	109
102	110	104	105	108	109
108	110	110	111	111	105
110	114	113	114	114	112
114	115	111	110	115	115

Grayscale Image After Fuzzy Adjustment



Illumination-Based Thresholding Process

1	0	0	0	0	0
0	0	1	1	0	0
0	0	1	1	0	0
0	0	0	0	0	1
0	0	0	0	0	0
0	0	1	1	0	0

Thresholded Binary Image

Figure 5.32 Illumination-Based Thresholding Process

Step 7:

When the thresholding of all the three areas is completed, the defects in the image can be recognized and the defect percentage can be calculated by counting the percentage of the defect pixels out of all the pixels in the image. Figure 5.33 illustrates the defect recognition and calculation.

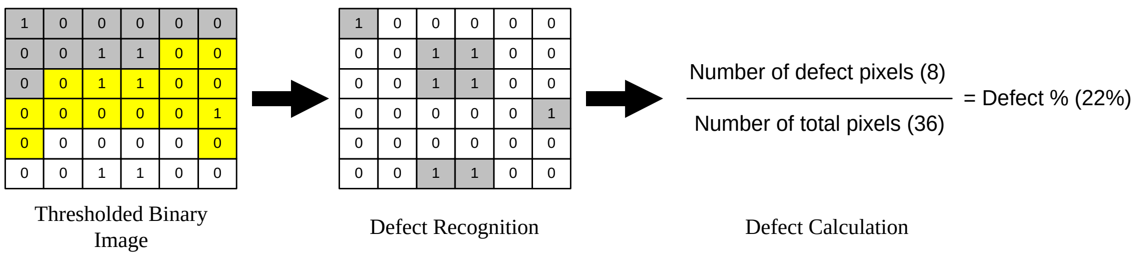


Figure 5.33 Defect Recognition and Calculation

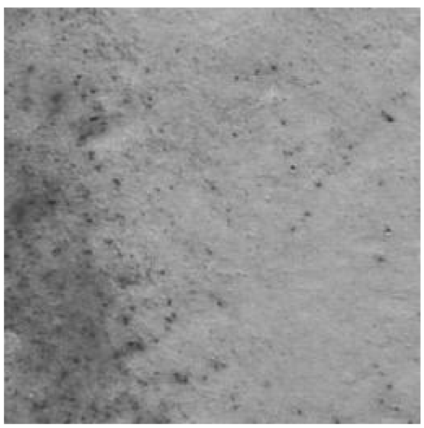
5.7 Applications of Neuro-Fuzzy Recognition Approach

In this section, color rust images will be recognized using the neuro-fuzzy recognition approach (NFRA). The training and target sets for the artificial neural network both contain 45 data. In other words, there are 45 training pairs for the artificial neural network.

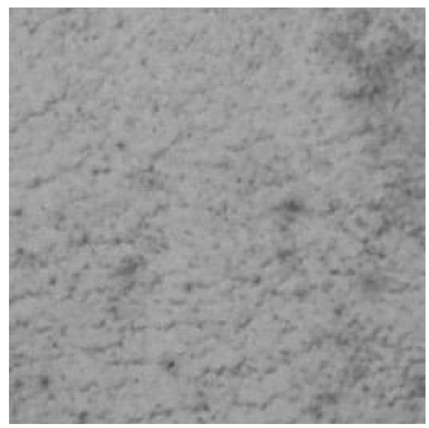
Figure 5.34 and Figure 5.35 demonstrate the processed binary image outputs using NFRA. The results indicate that the NFRA approach performs effectively in rust image recognition. However, it should be noted that the contrast between the rusts and the background is significant to the accuracy of the processed results. Sharp contrast usually leads to better results.

(a1) Original Color Image

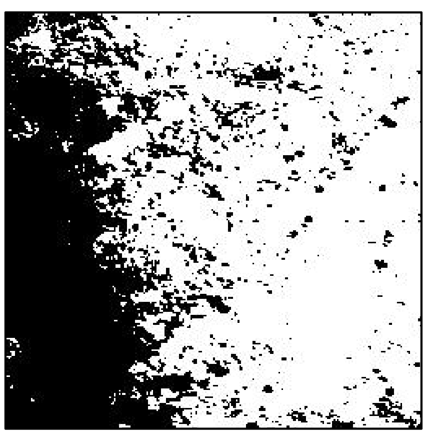
(b1) Original Color Image



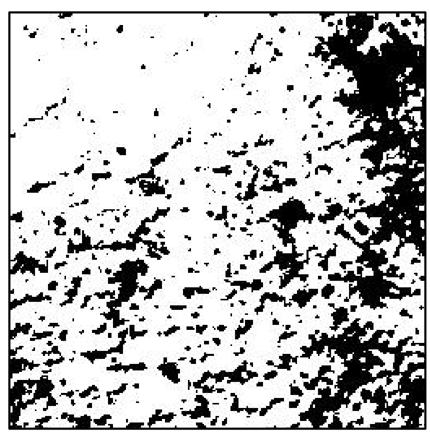
(a2) Grayscale Image



(b2) Grayscale Image



(a3) Binary Image

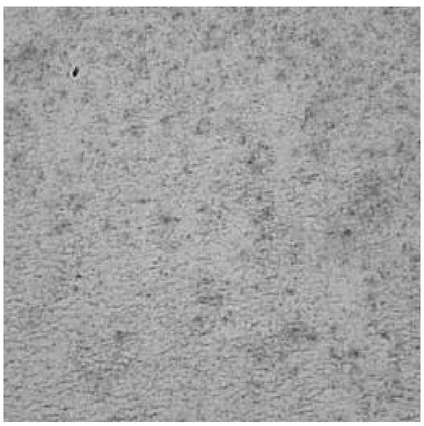


(b3) Binary Image

Figure 5.34 NFRA Processed Results (I)

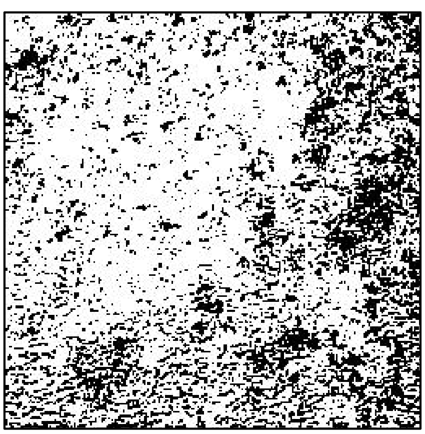
(a1) Original Color Image

(b1) Original Color Image

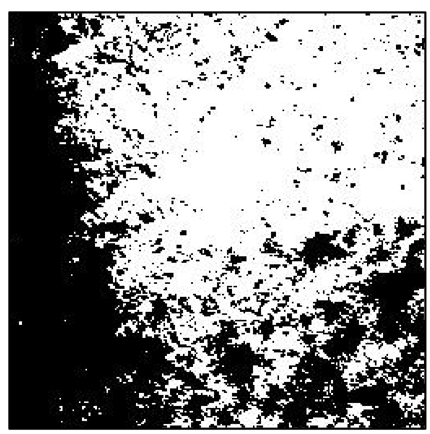


(a2) Grayscale Image

(b2) Grayscale Image



(a3) Binary Image



(b3) Binary Image

Figure 5.35 NFRA Processed Results (II)

5.8 Summary of Chapter

This chapter described the neuro-fuzzy recognition approach (NFRA) in detail. Starting from its theoretical background, artificial neural networks, fuzzy logic systems, the K-means algorithm, image thresholding, construction of the NFRA approach were introduced in this chapter. Afterward, methodology of the NFRA approach, the training of the artificial neural network, and the procedures of the fuzzy adjustment were explained, followed by demonstration of the stepwise neuro-fuzzy recognition model. The stepwise neuro-fuzzy recognition model, which was based on the NFRA approach, was developed to implement the NFRA approach in practice. Applications of the NFRA approach to rust image recognition were also given with limited samples. To fully apply the approach in practice for bridge painting rust inspection further research is needed before NFRA can be recommended for implementation.

CHAPTER VI

THE 1ST EXTENSION STUDY

6.1 Introduction

Before completing the NFRA study, INDOT SAC (Study Advisory Committee) members requested that the NFRA approach be further investigated for facilitating pragmatic implementation. Thus, this project was extended to meet SAC members' requests. The 1st extension study includes the effects of angles and distances, clean and non-clean surfaces, and light and dark conditions on the quality of images captured.

6.2 Research Objective

The research was to further assess the Neuro-Fuzzy Recognition Approach (NFRA) that is able to automatically determine rust percentage of highway steel bridge coating. NFRA system utilizes image processing, segmentation, fuzzy set and neural networks as a tool for percent rust determination.

The research studied the degree of the accuracy of the NFRA system under various conditions. Various conditions can happen when taking steel bridge painting images. And, they may affect the quality of images and consequently the rust percentage determination.

The main objective of this extended study was to find out what degree of the effect on the captured images resulted from different conditions: brightness, angle, distance, and cleanness.

6.3 Hypothesis

To facilitate the study, the definition for the four conditions comprising of brightness, angles, distance, and cleanness was made in advance. Meanwhile, a number of assumptions have been made for the measurement and comparison of each condition. The definitions and assumptions with regard to each condition are described as follows.

1. Brightness

To take images from light or dark conditions, appropriately designed criteria have to be made first. In other words, specific criteria have to be set up in order to distinguish brightness or darkness. The unit of lux is often used as a way of light measurement. Lux can be described as illuminance produced on a surface of area 1 square meter by a luminous flux of 1 lumen uniformly distributed over that surface (Satel-light 2002). Lux measures the amount of light in terms of a surface; not a light source. Therefore, the use of lux could suit to the needs of this research. Specially designed equipment called illuminometer can be used to measure lux. In addition, a photovoltaic sensor can measure the light levels and it can also provide accurate digitalized numbers. Table 6.1 shows typical lux numbers.

Table 6.1 Typical Lux Numbers (Micron 2002)

Type of Light	**Lux**
Direct sunlight	100,000 – 130,000 lx
Full daylight, indirect sunlight	10,000 – 20,000 lx
Overcast day	1,000 lx
Indoor office	200 – 400 lx
Very dark day	100 lx
Twilight	10 lx
Deep twilight	1 lx
Full moon	0.1 lx
Quarter moon	0.01 lx
Moonless clear night sky	0.001 lx
Moonless overcast night sky	0.0001 lx

Table 6.1 shows the different light levels. The numbers above 10,000 lux can be considered as light situation, and the ones below 10,000 lux as dark conditions in this study.

2. Angle

Another study is to examine whether or not different angles affect the results of image processing. To exemplify the process, three angles are selected, which are 45, 60, and 90 degrees. Figure 6.1 shows the direction of cameras taking images in different angles.

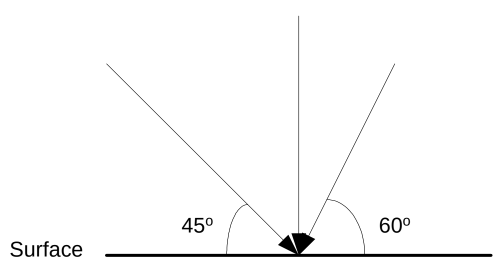


Figure 6.1 Three Different Angles

3. Distance

Digital images are always taken at a distance near 3 feet in the previous studies. The images from this close distance provide clearer steel bridge painting surface condition. 3 feet is defined as short distances, while 10 feet is defined as long distance for this expanded study. The comparison from two different distances will be made.

4. Cleanness

There seems to be no clear-cut scientific approach to measure "Cleanness". The correspondence with INDOT and FHWA engineers showed that they do not clean steel bridge surface between coats. Steel bridges are cleaned with medium pressure water in surface preparation for putting the primer coat on. ASTM D 3276 describes that many different materials shall be removed during surface preparation stage since those materials will severely affect the quality of the coating (ASTM 2000). Those materials include oil, grease, soil, weld spatter, and slag. In order to evaluate the degree of cleanliness, appropriately designed rating scale needs to be set. ASTM E 1671 specifies the rating scale of office facility to meet certain possible requirements for cleanliness (ASTM 1999). The scale is divided into nine levels, and classified to five areas of outside and inside facility. Five areas are exterior and public areas, office areas (interior), toilets and washrooms, special cleaning, and waste disposal for building. To suit the purpose of this study, the ASTM E1671 scale for exterior and public areas has been modified. Table 6.2 shows the suggested rating scale. Based on the suggested scale table, the rating higher than or equal to level 5 could be considered as clean. In other words, it is non-clean below level 5. Based on this set criteria for cleanness, the images taken from this defined clean surfaces or non-clean surfaces will be compared in the analysis stage of this study.

Table 6.2 Suggested Cleanness Rating Scale

Level	Description
9	The surface is very clean, fresh-looking. The surface is totally free of dirt and accumulated materials such as oil, grease, soil, weld spatter, and slag.
7	The surface is uniformly clean. The surface is free of loose dirt and has minimal accumulated materials.
5	The surface is fairly clean. The surface is mostly free of loose dirt. There are some stains and accumulated materials.
3	The surface is generally dirty. The surface has some loose dirt and many accumulated materials. The surface is smudgy in appearance.
1	The surface is very dirty. The surface has much loose dirt and extremely many accumulated materials. The surface is dusty, streaked, and grimy.

6.4 Research Methodology

The research can be divided into 6 steps as follows:

Step 1: To select a target area of 10 cm x 10 cm from a dusty and slightly rusty steel beam coated with protection paint is the first step for reexamining the NFRA system as SAC requested. Images with different conditions are then be acquired from this designated location. Image acquisition has to be performed on a sunny day for good-quality images.

Step 2: The second step is to take images from this dusty and slightly rusty steel surface. The distance has to be kept 3 feet from the surface. After taking five images from the target-squared area, cleaning will be performed. The cleanness is based on pre-planned rating scale when the surface is cleaned to the degree above level 5 as specified in Table 6.2.

Step 3: After the level of cleanness is satisfied, the third step is to take images from light or dark conditions. Images are acquired on a bright day for good-quality images. So, taking images in light conditions seems to be no problem. An additional device could be designed in order to create dark conditions. Figure 6.2 shows the way to create a dark condition using a black box that is able to block direct and reflected light.

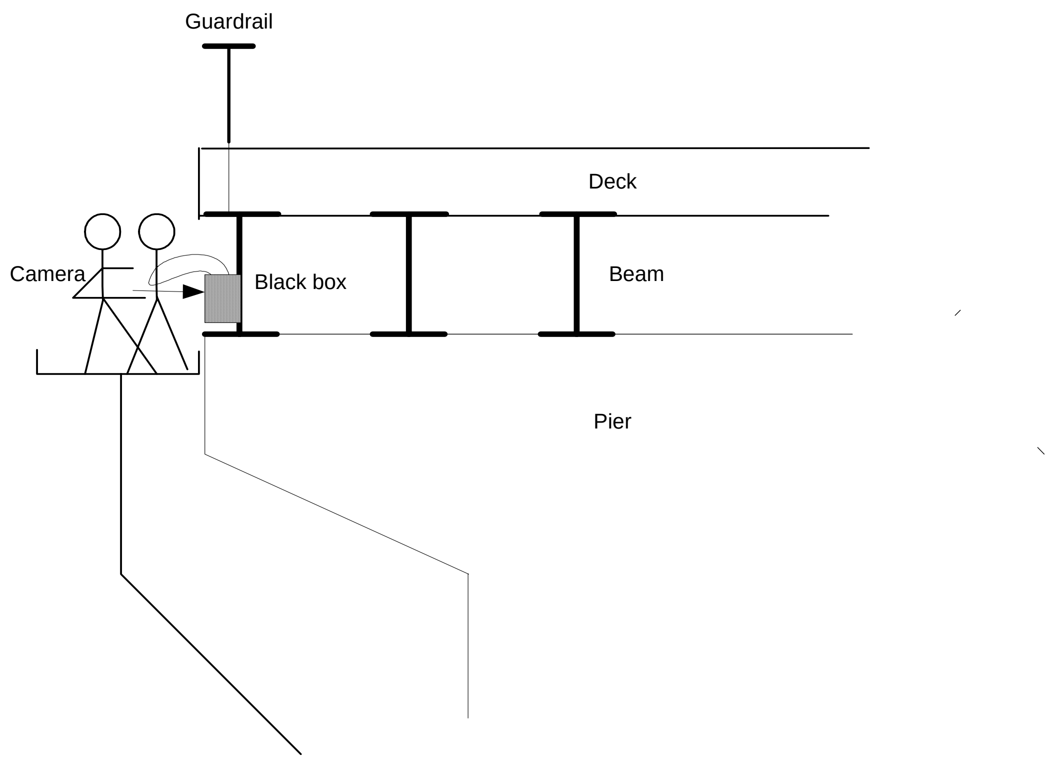


Figure 6.2 Dark Condition Creation

Step 4: Fourth step is to find out the effect of distances and angles. As discussed earlier, images are taken from two different distances; short and long, and three different angles, 45, 60, and 90 degrees. Regarding distances, 3 feet is defined as short distance and 10 feet as long distance. For this task, camera positioning is an important factor for acquiring images in terms of accuracy. Figure 6.3 suggests a camera positioning, and the numbers in hexagons indicates the sequential order (See Appendix F).

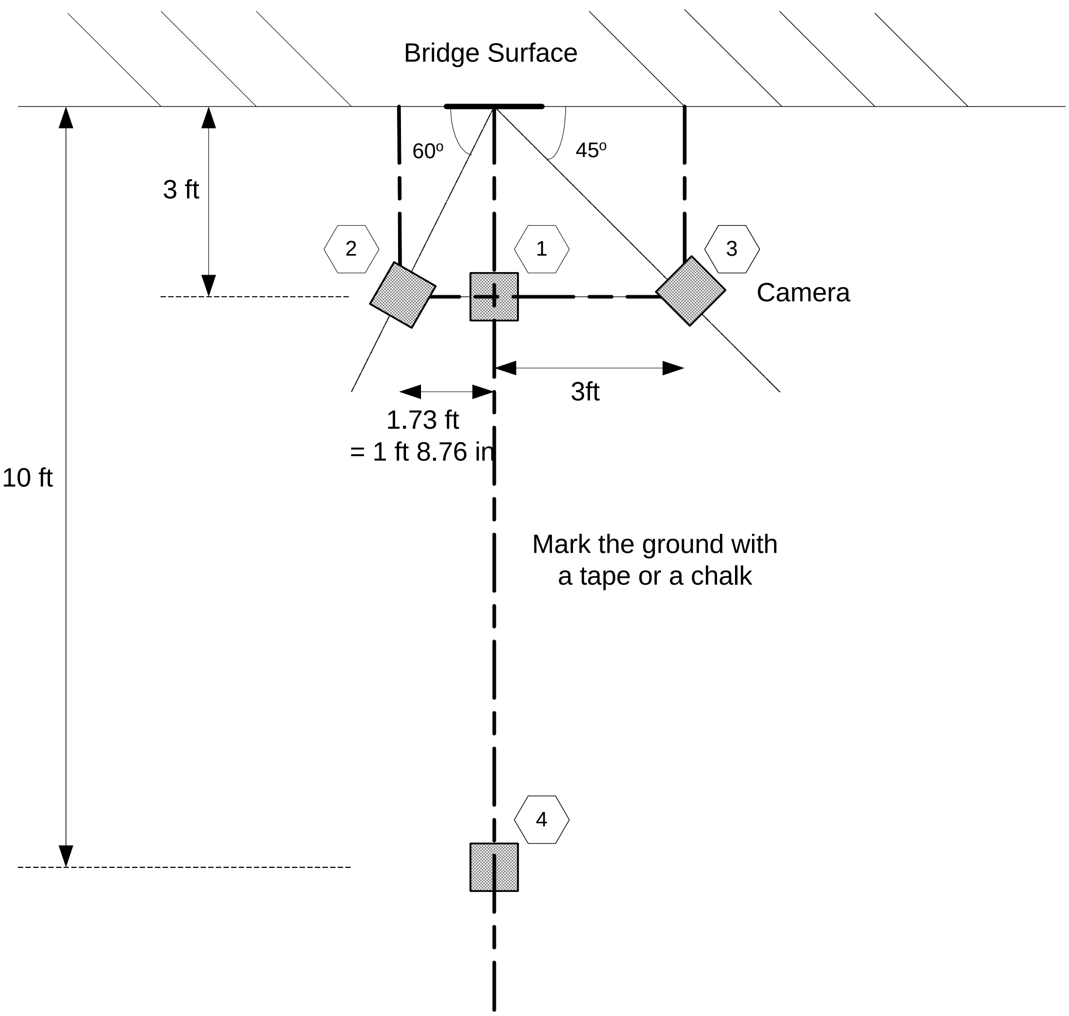


Figure 6.3 Camera Positioning

Step 5: After the images taken, it is ready to get into the image analysis phase. Before the image analysis starts, all images should be transferred from the digital camera to the computer that runs the NFRA system. And then, an additional work has to be performed in order to crop the same target area from a whole captured image for late validity comparison. The images are then adjusted to have dimensions of 256x256 pixels for image processing. Many commercial software products like Photoshop and Megaview support that cropping task.

Step 6: The final step is to run the NFRA program on all captured images and determine the rust percentages and processing time.

6.5 Analysis

Once the image acquisition and computer transfer were completed, the images were processed and analyzed. Images taken at 90-degree, 60-degree, and 45-degree angles, and from short (3ft) and long (10 ft) distances, under bright and shaded/dark, and clean and non-clean conditions were analyzed image by image. Then, rust percentage and processing time of all images were determined.

Rust images were processed through NFRA (Neuro-Fuzzy Recognition Approach). Three other methods were used to validate the results of NFRA. They are: ISKA (Illumination-based Segmentation and K-means Algorithm), KMNS (K-means Algorithm), and SKMN (Simplified K-means Algorithm). Figure 6.4 depicts the procedural structures of these four methods. NFRA, ISKA, and KMNS segment a whole image into three areas before recognizing defects and non-defects. SKMN, however, processes a whole image directly; no segmentation is made. Moreover, NFRA and ISKA are based on three illumination values for the analyses to proceed, while KMNS does not depend on any illumination values to proceed like SKMN. Rust percentage and CPU time were obtained using four techniques from all captured images. Rust images were captured from an outdoor beam behind Civil Engineering building in Purdue University campus for this experimental study. Table 6.3 shows the results of all processed images, and Appendix G lists all the corresponding processed images. Table 6.4 and 6.5 show the mean values and standard deviations in terms of rust percentage and CPU processing time.

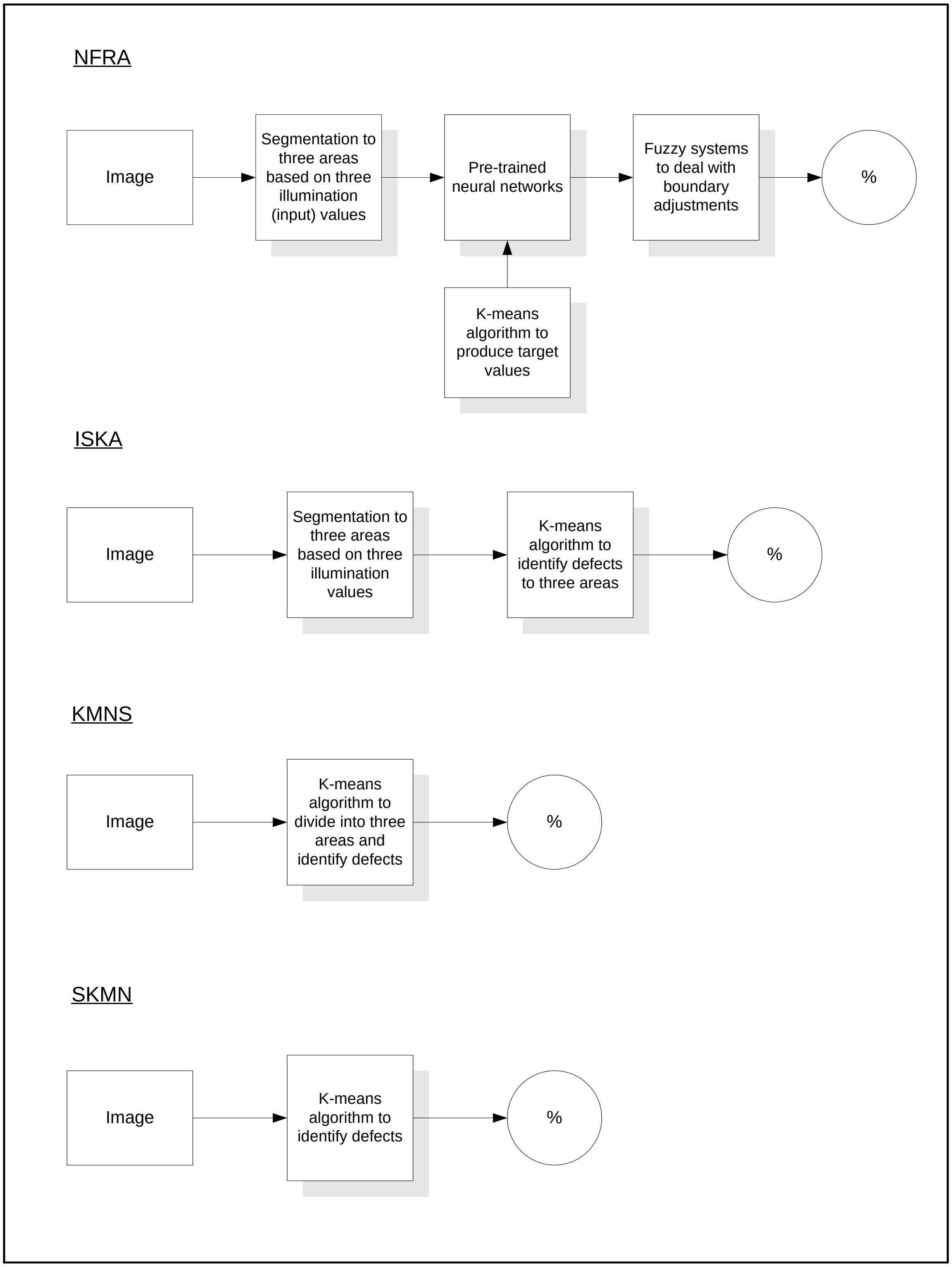


Figure 6.4 Procedures of Four Techniques

Table 6.3 Results of Processed Images

Image	NFRA		ISKA		KMNS		SKMN	
	RP (%)	CPU (Sec)	RP (%)	CPU (Sec)	RP (%)	CPU (Sec)	RP (%)	CPU (Sec)
Right angle/ Non-clean								
1	19.80	210	11.37	290	5.64	45	5.53	30
2	44.28	210	13.12	273	4.90	60	4.79	20
3	70.09	225	16.94	290	5.57	93	5.08	23
4	20.15	195	13.32	258	4.72	44	4.64	21
5	31.81	258	12.70	320	4.79	50	4.72	22
60-degree/ Non-clean								
1	16.17	205	9.36	252	4.75	45	4.65	20
2	56.78	230	11.56	277	4.91	64	4.81	15
3	30.31	287	9.93	342	4.73	49	4.63	25
4	48.04	220	10.37	270	4.84	73	4.73	22
5	68.19	227	12.33	270	5.64	85	5.64	15
45-degree/ Non-clean								
1	12.57	265	9.12	325	5.41	34	5.11	22
2	14.16	233	8.47	308	4.64	40	4.64	20
3	30.81	309	8.34	388	4.51	35	4.45	15
4	6.77	232	5.24	308	4.46	26	4.46	21
5	13.63	218	9.97	288	4.75	36	4.75	18
Long distance/ Non-clean								
1	28.57	219	10.93	268	4.80	51	4.67	18
2	17.43	208	9.65	290	5.97	35	5.60	25
3	74.98	153	11.78	198	6.32	62	6.32	28
4	86.14	201	11.41	260	6.50	51	6.50	18
5	16.52	233	8.54	275	6.77	35	6.59	30
Shading/ Non-clean								
1	99.61	244	67.25	417	99.61	18	2.66	48
2	99.61	399	60.90	532	99.61	25	1.90	37
3	99.61	305	61.67	355	99.61	25	2.05	35
4	99.61	435	61.09	493	99.61	24	2.30	30
5	99.61	258	44.20	300	3.38	78	3.03	27
Right angle/ Clean								
1	12.18	103	5.70	267	5.08	35	4.98	25
2	11.47	222	7.01	298	5.15	40	5.04	21
3	15.08	157	6.18	275	5.22	41	5.11	21
4	14.36	189	7.67	240	5.70	47	5.70	26
5	15.18	170	8.06	228	6.28	39	6.14	24
60-degree/ Clean								
1	45.42	175	12.15	255	6.63	61	6.24	21
2	46.74	190	10.88	316	6.67	51	6.49	25
3	22.89	170	9.05	308	5.52	48	5.39	24
4	36.02	146	11.56	276	6.12	61	5.75	25
5	31.26	172	10.85	313	6.34	52	5.91	22
45-degree/ Clean								
1	7.11	207	5.56	290	5.11	42	5.21	13
2	9.32	248	7.72	312	5.69	32	5.69	21
3	11.60	279	8.82	370	6.21	37	6.21	21
4	13.57	313	8.16	379	6.04	37	6.04	23
5	12.45	274	8.05	345	6.02	32	6.02	21
Long distance/ Clean								
1	74.23	228	13.62	286	6.73	57	6.24	22
2	29.83	222	13.40	289	6.00	44	5.78	25
3	10.40	137	7.32	203	5.60	34	5.60	28
4	21.92	210	9.05	277	6.12	26	6.12	26
5	71.72	232	14.04	317	6.96	57	6.45	26

Table 6.4 Mean and Standard Deviation (SD) of Rust Percentage

Image	NFRA		ISKA		KMNS		SKMN	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Right angle /Non-clean	37.23	20.94	13.49	2.07	5.12	0.44	4.95	0.36
60-degree /Non-clean	43.90	20.78	10.71	1.21	4.97	0.38	4.89	0.42
45-degree /Non-clean	15.59	9.01	8.23	1.79	4.75	0.38	4.68	0.27
Long distance /Non-clean	44.73	33.29	10.46	1.34	6.07	0.76	5.94	0.81
Shading /Non-clean	99.61	0	59.02	8.69	80.36	43.03	2.39	0.21
Right angle /Clean	13.65	1.72	6.92	0.99	5.49	0.51	5.39	0.51
60-degree /Clean	36.47	9.97	10.90	1.16	6.26	0.47	5.96	0.43
45-degree /Clean	10.81	2.59	7.66	1.24	5.81	0.44	5.83	0.40
Long distance /Clean	41.62	29.46	11.49	3.08	6.28	0.55	6.04	0.34

Table 6.5 Mean and Standard Deviation (SD) of CPU Time

Image	NFRA		ISKA		KMNS		SKMN	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Right angle /Non-clean	219.6	23.94	286.2	23.13	58.4	20.35	23.2	3.96
60-degree /Non-clean	233.8	31.27	282.2	34.69	63.2	16.62	19.4	4.39
45-degree /Non-clean	251.4	36.51	323.4	38.42	34.2	3.19	19.2	2.77
Long distance /Non-clean	202.8	30.35	258.2	35.41	46.8	11.67	23.8	5.59
Shading /Non-clean	328.2	85.11	419.4	95.53	34.0	24.77	35.4	8.08
Right angle /Clean	168.2	43.89	261.6	27.97	40.4	4.33	23.4	2.30
60-degree /Clean	170.6	15.84	293.6	26.86	54.6	6.02	23.4	1.82
45-degree /Clean	264.2	39.47	339.2	37.84	36.0	4.18	19.8	3.90
Long distance /Clean	205.8	39.35	274.4	42.62	43.6	13.79	25.4	2.19

To examine the validity of the four methods, the ability to recognize rust percentage was examined by using ASTM standard images (ASTM 1995). ASTM provides rust image templates so that bridge inspectors can determine rust percentage through their eyeball comparison. 1%, 3%, and 10% rust images were chosen and processed through the programs of the four methods. Figure 6.5 shows the patterns of rust images and their corresponding percent rust that ASTM provides.

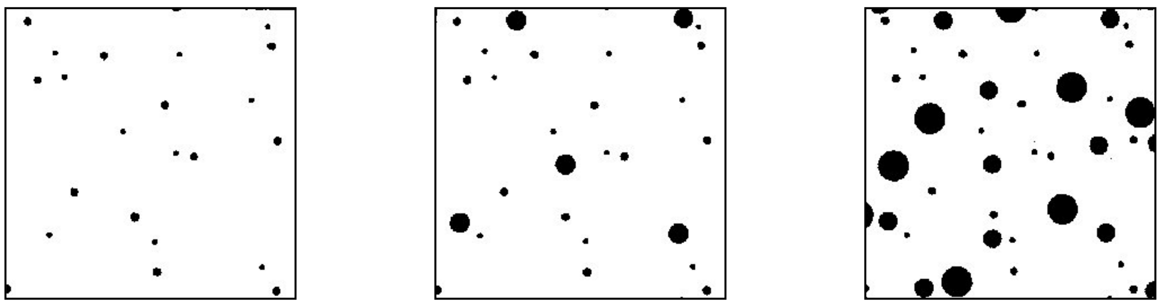


Figure 6.5 ASTM Rust Standard Images (1%, 3%, and 10%)

Each image was processed two times, and rust percentage and CPU time were calculated. Table 6.6 shows the processed results. From the results, KMNS and SKMN still show good performances. SKMN performed especially well, recognizing all images within a very short time. All processing time was less than or equal to 10 sec. KMNS and SKMN showed almost the same rust percentages as ASTM's although they are slightly higher than rust percentages provided by ASTM. This fact might come from the process to crop images after ASTM percent rust patterns are scanned into computer. The cropped area may not be exactly same every time. Nevertheless, the processed results are very close to the standard rust percentages. On the other hand, NFRA and ISKA failed to determine rust percentages because both methods include segmentation process in which an image is divided into 3 areas based on 3 illumination values. However, ASTM sample templates simply comprise of black and white colors, and therefore they cannot generate three illumination values.

Table 6.6 Results of Processed Images using ASTM Standard

Image		NFRA		ISKA		KMNS		SKMN	
		RP (%)	CPU (Sec)	RP (%)	CPU (Sec)	RP (%)	CPU (Sec)	RP (%)	CPU (Sec)
1	1% Rust	N/A	N/A	N/A	N/A	1.14	20	1.14	7
	3% Rust	N/A	N/A	N/A	N/A	3.03	21	3.03	6
	10% Rust	N/A	N/A	N/A	N/A	10.36	20	10.36	6
2	1% Rust	N/A	N/A	N/A	N/A	1.14	20	1.14	9
	3% Rust	N/A	N/A	N/A	N/A	3.03	21	3.03	10
	10% Rust	N/A	N/A	N/A	N/A	10.36	20	10.36	10

6.6 Finding and Discussion

Some findings from the experimental results can be discussed as follows.

♦ Four techniques used in this study failed to recognize the rust images under shading conditions. The results are all inconsistent and invalid. It means that images should not be captured from dark areas or under poor weather conditions.

♦ ISKA took the longest time to process images, while SKMN, the simplest one, took the shortest time on the whole. NFRA is second, and KMNS is third.

♦ In this study, KMNS and SKMN produced very stable results in terms of rust percentage and CPU time under all conditions except shading condition. Standard deviations for rust percentages and CPU time were also very low. But, NFRA and ISKA generated inconsistent results even under the same categories. KMNS and SKMN seem to be effective on rust recognition.

♦ In KMNS and SKMN, images taken from 90-degree, 60-degree, and 45-degree angles at a short distance have very close rust percentage results, but images taken from 90-degree angle at a long distance have slightly higher values. It seems that distances affect the results of rust percentages.

♦ From the results of KMNS and SKMN, rust percentages from non-cleaning groups are generally higher than those from cleaning groups. It means that cleaning work has an effect on the rust percentage calculations, and therefore both groups showed different results. But, it is still not certain because non-clean images and clean images were taken at different days even if two days had similar weather conditions. The study about the effect of cleaning needs to be further examined.

6.7 Summary of Chapter

The research findings can be summarized as follows:

1) The NFRA method was further examined and compared with other three methods; ISKA, KMNS, and SKMN.
2) The rust images were taken from a real steel beam coated with light blue protection paint. To assure the consistency, the images were taken from the same 10 cm x 10 cm squared area and cropped into 256x256 pixels constantly (See Appendix F).
3) The results of the rust percentage obtained from the four methods show that NFRA generally has the highest value and SKMN has the lowest value. The results from ISKA and KMNS fall between them. For instance, under a right angle and non-clean situation, the mean rust is 37.23 % for NFRA; 13.49 % for ISKA; 5.12 % for KMNS, and 4.95 % for SKMN (See Table 6.4).
4) The CPU time needed for image processing and rust percentage determination demonstrates the similar order as the percent rust results. ISKA takes the longest time; NFRA the second, and then KMNS. SKMN takes the least time (See Table 6.5).

5) The results of rust percentage are nearly the same even though the images are taken from 90-degree, 60-degree, or 45-degree angles (See Table 6.4).

6) The cleanness of the steel surface has a slight impact on the percent rust determination. Seemingly, the images taken after the coated steel surface on the beam was cleaned result in a little bit higher percent rust (See Table 6.4).

7) The percent rust results obtained under shaded conditions were inaccurate even though images were taken under clean or non-clean conditions. The results are inconsistent and invalid (See Table 6.4).

8) Right angle images were taken from 3 feet away and 10 feet away. The images taken from 10 feet (long distance) turn out high value of percent rust. They are: 5.94 % for 10 feet/non-clean, 4.95 % for 3 feet/non-clean, 6.04 % for 10 feet/clean, and 5.39 % for 3 feet/clean. It looks like the position of the camera at various angles has a slight impact on the determination of percent rust (See Table 6.4).

9) By carefully examining the percent rust results and these corresponding images after the color image data were processed into binary images, the patterns of binary images from KMNS and SKMN methods are definitely close to their original color images (See Appendix G).

10) To examine the validity of the four investigated methods; NFRA, ISKA, KMNS, and SKMN, ASTM standard percent rust templates were used. The squared black and white percent rust figures provided by ASTM for painting inspectors were processed through programs of the four investigated methods respectively (See Figure 6.5). The percent rust resulted from KMNS and SKMN methods are nearly the same as the standard rust percentages specified by ASTM. Since there are only two illumination

values on the ASTM black and white contrast figures, NFRA and ISKA are not applicable to these cases. This testing and the results comparing with ASTM standard templates significantly demonstrate the validity of the percent rust obtained from KMNS and SKMN (See Table 6.6).

11) Considering the CPU time used for image processing and percent rust determination, SKMN consistently outplays KMNS (See Table 6.6).

12) Therefore, based on the validity of determining percent rust and CPU time used, it is likely to be concluded that SKMN is the best among the four investigated methods, and recommended for implementation. NFRA, ISKA, and KMNS are still in research stage for experimenting segmentation into three areas. Further research is still needed before they can be recommended for implementation.

CHAPTER VII

THE 2ND EXTENSION STUDY

7.1 Introduction

As the SKMN (Simplified K-Means Algorithm) method showed the best performance among the four investigated methods, further investigation on the SKMN was needed. Moreover, implementation procedures for the SKMN need to be developed before launching demonstration projects.

7.2 Research Objective

For the 2nd extension study, SAC members set seven objectives. They are:

1) Statistical testing that needs to be performed for confirming whether or not the angles, distance, and cleanness have significant effects on the rust percentage determination;

2) Examination of allowable tolerances for the results of rust percentages in terms of angles, distances, and cleanness;

3) Determination of distance factors for the percent rust results obtained from various distances;

4) Trial use of infrared, refracting lenses, or other optical devices for capturing images under shaded and/or dark situations;

5) Development of a simple and reliable procedure for randomly sampling the images from a steel bridge;

6) Development of a step-by-step procedure to use a digital camera and/or a digital camcorder for capturing the randomized paint images. Meanwhile, screen-by-screen,

command-by-command instructions to process the images and to determine the percent rust for each image should be documented in detail; and

7) Providing a new warranty clause for the use by INDOT Division of Operations Support to assure the quality of INDOT steel bridge painting jobs and using the determined percent rust to assist INDOT painting inspectors on accepting or rejecting the quality.

7.3 Statistical Testing

7.3.1 Methodology for objective (1) and (2)

To achieve the objective (1) and (2), the method was divided into 6 steps as follows:

Step 1: Selecting a target area of 10cm x 10cm from a dusty and slightly rusty steel beam coated with protection paint is the first step for examining the SKMN method as SAC requested. Images with different conditions were obtained from this designated location. Image acquisition was performed on November 1, 2002. It was a sunny day, and the lux number on the coating surface was 10,400 lux. Lux is the unit for measuring the amount of light in terms of a surface, not a light source.

Step 2: The second step was taking images from this dusty and slightly rusty steel surface. First, thirty images were taken from different angles: 90-degree, 60-degree, and 45-degree respectively, while keeping the distance of 3 feet constant. And then, another thirty images were taken at 90-degree/10 feet. Images are supposed to be taken from different distances: short and long. Three feet is defined as a short distance and 10 feet as a long distance. For this task, camera positioning could be an important factor for acquiring images as exactly as possible. Figure 7.1 shows the camera positioning work plan, and the numbers in circles (①, ②,③, and④) indicate the sequential order.

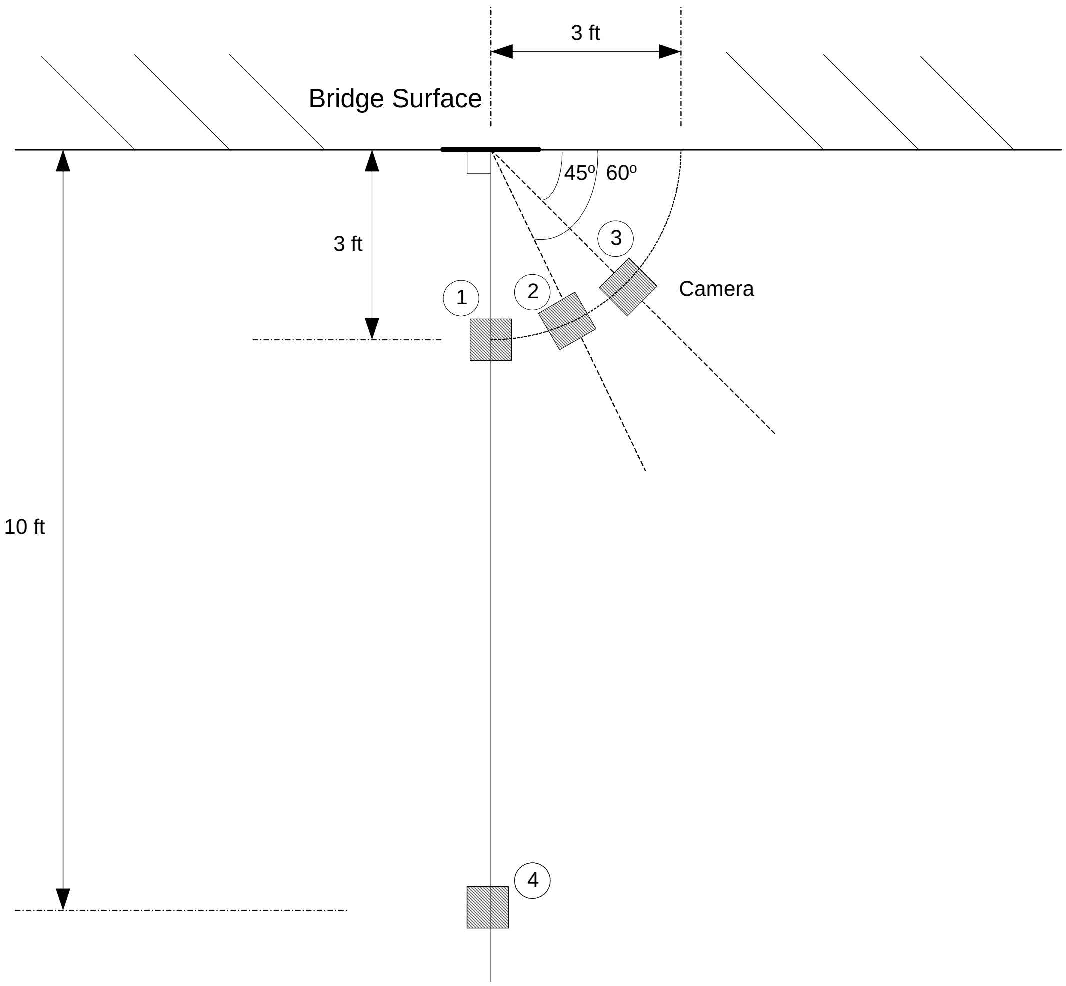


Figure 7.1 Camera Positioning Plan

Step 3: After completing the image acquisition under non-clean conditions, the surface was cleaned. The coated steel surface was wiped with a wet towel. During the cleaning, a significant amount of dust, rust stains, and loose corrosion flakes were removed.

Step 4: The fourth step was taking images from the cleaned surface. The image acquisition process and number of images were exactly same with Step 2. Step 4 is the process that repeats Step 2.

Step 5: After all the images were taken, image analysis was performed. Before the image analysis started, all images were transferred from the digital camera to the computer that runs the SKMN system. And then, additional work had to be performed in order to crop the same target area from a whole captured image for late validity comparison. The images were then adjusted to have dimensions of 256 x 256 pixels for image processing. Many commercial software products like Photoshop and Megaview can perform the cropping task.

Step 6: The final step was to run the SKMN program on all captured images and determine the rust percentages and processing time.

7.3.2 Statistical testing and results

The detail rust percentages and CPU times obtained from the aforementioned methodologies can be found in the Appendix I. Table 7.1 and 7.2 summarize means and standard deviations (SDs) of the data shown in Appendix I.

Table 7.1 Mean and Standard Deviation (SD) of Rust Percentage

Condition	**Non-clean (%)**		**Clean (%)**	
	Mean	SD	Mean	SD
90-degree angle/ 3-foot distance	0.9358	0.0674	1.6910	0.0496
60-degree angle/ 3-foot distance	1.0138	0.0568	1.7342	0.0288
45-degree angle/ 3-foot distance	1.0337	0.0353	1.7530	0.0395
90-degree angle/ 10-foot distance	1.2231	0.2058	1.5221	0.0471

Table 7.2 Mean and Standard Deviation (SD) of CPU Time

Condition	**Non-clean (Sec)**		**Clean (Sec)**	
	Mean	SD	Mean	SD
90-degree angle/ 3-foot distance	19.7	3.1964	14.2	0.9353
60-degree angle/ 3-foot distance	19.1	2.9093	13.3	1.8631
45-degree angle/ 3-foot distance	19.2	1.4162	12.7	1.9357
90-degree angle/ 10-foot distance	26.3	6.8438	13.9	2.0902

Based on the calculated data of mean and standard deviation of rust percentage, z-statistical testing was performed to examine whether or not the angles, distance, and cleanness have significant effect on the rust percentage determination. The z-statistical testing procedures are as follows.

(1) H_0: $\mu_1 - \mu_2 = 0$, H_a: $\mu_1 - \mu_2 \neq 0$

(2) Reject if either $z \geq z_{\alpha/2}$ or $z \leq -z_{\alpha/2}$

- $z_{0.025} = 1.96$ when $\alpha = 0.05$
- $z_{0.005} = 2.575$ when $\alpha = 0.01$

(3) $z = \dfrac{\bar{x} - \bar{y}}{\sqrt{\dfrac{s_1^2}{m} + \dfrac{s_2^2}{n}}}$

(4) Accept or reject

F-statistical testing also was performed to know whether many standard deviations calculated from different conditions are same or not. The F-statistical testing procedures are as follows.

(1) H_0: $\sigma_1^2 = \sigma_2^2$, H_a: $\sigma_1^2 > \sigma_2^2$

(2) Reject if $f \geq F_{\alpha,m-1,n-1}$

- $F_{0.01,29,29} \approx 2.41$ when $\alpha = 0.01$, m = 30, and n=30

- $F_{0.05,29,29} \approx 1.85$ when $\alpha = 0.05$, m = 30, and n=30

(3) $f = s_1^2 / s_2^2$

(4) Accept or reject

The results of the z-test and F-test are developed in Table 7.3.

Table 7.3 Results of z-test and F-test

Condition		z-test			F-test		
		z value	α=0.01	α=0.05	f value	α=0.01	α=0.05
Non-clean	90^o vs. 60^o with 3 ft	-4.85	R	R	1.41	A	A
	90^o vs. 45^o with 3 ft	-7.05	R	R	3.65	R	R
	3 ft vs. 10 ft with 90^o	-7.27	R	R	9.32	R	R
Clean	90^o vs. 60^o with 3 ft	-4.13	R	R	2.97	R	R
	90^o vs. 45^o with 3 ft	-5.36	R	R	1.58	A	A
	3 ft vs. 10 ft with 90^o	13.52	R	R	1.11	A	A
Non-clean vs. Clean	90^o/3 ft	-49.4	R	R	1.85	A	A
	60^o/3 ft	-61.9	R	R	3.89	R	R
	45^o/3 ft	-74.4	R	R	1.25	A	A
	90^o/10 ft	-7.76	R	R	19.09	R	R
Note: R (Reject), A (Accept), α (Confidence level)							

7.3.3 Summary for objective (1) and (2)

The research findings can be summarized as follows:

(1) The rust images were acquired from a real steel beam in campus on November 1, 2002. To assure the consistency, the images were taken from the same 10cm x 10cm area and cropped into 256 x 256 pixels constantly.

(2) One target area from the steel beam surface was selected and thirty images from each of following conditions were taken. The total images taken are 240. The conditions can be categorized as "Non-clean" conditions (90-degree angle/3-foot distance; 60-degree

angle/3-foot distance; 45-degree angle/3-foot distance, and 90-degree angle/10-foot distance) and “Clean” conditions (90-degree angle/3-foot distance; 60-degree angle/3-foot distance; 45-degree angle/3-foot distance, and 90-degree angle/10-foot distance).

(3) The statistical testing showed that the rust percentages from 90-degree angle and 60-degree angle are different on 95% and 99% confidence level for both of non-clean and clean surface cases.

(4) The statistical testing showed that the rust percentages from 90-degree and 45-degree angle are different at 95% and 99% confidence level in both cases, non-clean and clean surfaces.

(5) The statistical testing also indicated that the rust percentages from short distances and long distances are different on 95% and 99% confidence level for both cases; non-clean and clean surfaces. It should be noted that mean rust percentage from long distance, 1.2231%, is much higher than that from short distance, 0.9358%, under non-clean conditions. On the contrary, mean rust percentage from long distance, 1.5221%, is lower than that from short distance, 1.6910%, under clean conditions. The reason could be that some materials, such as rust stain and dust, severely affect the determination of rust percentage under non-clean conditions. Thus, it may generate higher values. But, under clean conditions, the effect of such materials was removed. The process produces more stable rust percentages with small standard deviation, 0.0471%.

(6) The results of the statistical testing reveal that the rust percentages from non-clean conditions and clean conditions are different at 95% and 99% confidence level in all conditions. The different results can be easily predicted by looking at the color images (See Appendix J and K). Mean rust percentages under clean conditions are much higher

than those under non-clean conditions in all the cases. The best reason is that some dirty materials on the steel beam surface and loose flakes from corrosion were removed from the cleaning work. By carefully examining the processed images, the images from clean conditions reflect the original color images better.

(7) Images under clean conditions take less time to process for all conditions.

(8) Based on the determination of rust percentage and statistical testing, it can be concluded that if steel surfaces are cleaned, the results are significantly different. The angles and distances also affect the results of rust percentage determination.

7.4 Determination of Distance Factors

7.4.1 Methodology

The objective is to determine the distance factors for the percent rust results obtained from various distances. For the extensive study, various distances were selected from 10, 15, 30, 45 to 60 feet as shown in Figure 7.2. Thirty images were taken from those respective different distances, and then processed by using the SKMN method to calculate rust percentages. The rust percentages depending on the distances were investigated and compared with each other.

To reconfirm the validity and feasibility of this experiment, the enlarged ASTM standard images were applied for image acquisition. Three image templates having the rust of 0.1%, 0.3%, and 1% were used and the acquired images were processed through the SKMN method (See Figure 7.3). Fairly low rust values were selected because INDOT specified no repair work is necessary in case of rust less than 0.3%. Table 3.1 provides the estimated repair area in terms of rust percentage.

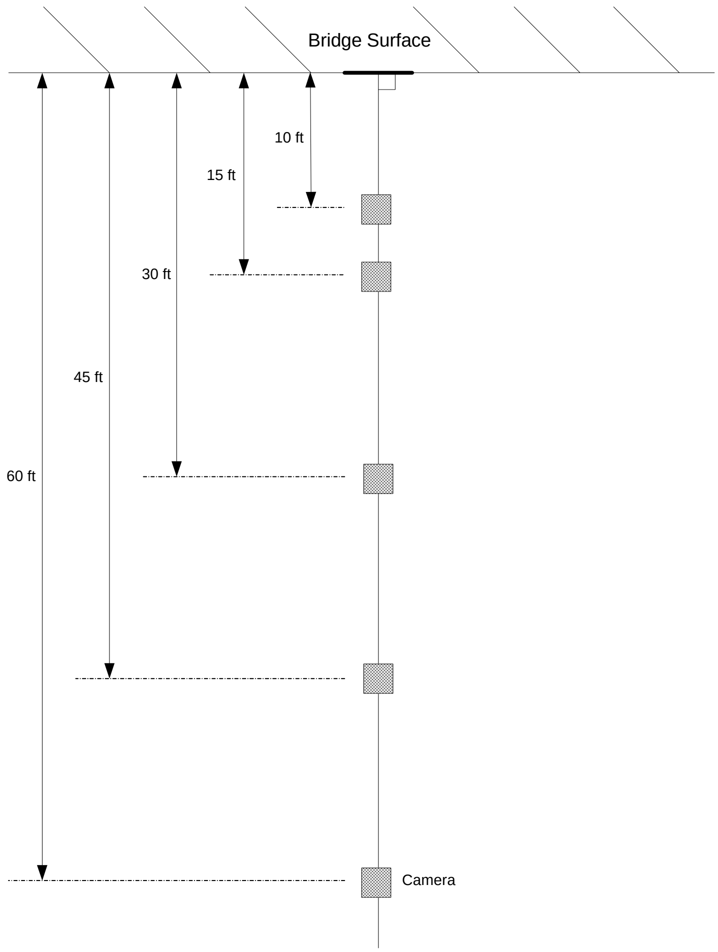


Figure 7.2 Image Capture Plan for Distance Factor Study

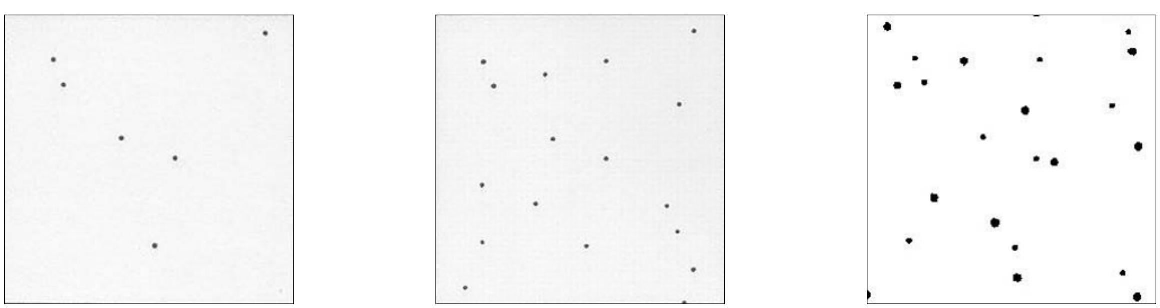


Figure 7.3 ASTM Standard Images (0.1%, 0.3%, and 1% from left)

Table 7.4 Estimated Area to be Repainted

Corrosion rating	Description	Area to be painted (%)	Rust percent range (x)
10	No rust or less than 0.01% rust	0	$0 \leq x < 0.01$
9	Minute rust, less than 0.03% rust	0	$0.01 \leq x < 0.03$
8	Few isolated rust spots, less than 0.1% rust	0	$0.03 \leq x < 0.1$
7	Less than 0.3% rust	0	$0.1 \leq x < 0.3$
6	Extensive rust spots, less than 1% rust	8	$0.3 \leq x < 1$
5	Less than 3% rust	18	$1 \leq x < 3$
4	Less than 10% rust	40	$3 \leq x < 10$
3	Approximately 1/6 of surface rusted	60	$x \cong 16.7$
2	Approximately 1/3 of surface rusted	100	$x \cong 33.3$
1	Approximately 1/2 of surface rusted	100	$x \cong 50$
0	Approximately 100% of surface rusted	100	$x \cong 100$

Table 7.5 shows the different light levels as expressed in terms of “Lux.” As the numbers above 10,000 lux were determined as light situation, image acquisition was performed at the days having over 10,000 lux.

Table 7.5 Different Light Levels

Type of Light	**Lux**
Direct sunlight	100,000 – 130,000 lx
Full daylight, indirect sunlight	10,000 – 20,000 lx
Overcast day	1,000 lx
Indoor office	200 – 400 lx
Very dark day	100 lx
Twilight	10 lx
Deep twilight	1 lx
Full moon	0.1 lx
Quarter moon	0.01 lx
Moonless clear night sky	0.001 lx
Moonless overcast night sky	0.0001 lx

7.4.2 Experimental results

All images taken from three different image templates were transferred to a personal computer and processed using the digital image processing method of SKMN. The mean rust percentages from 0.1%, 0.3%, and 1% ASTM templates are presented in Table 7.6, 7.7, and 7.8, respectively. Figure 7.4, 7.5, and 7.6 show the changes of rust percentages according to the distances graphically. The detailed rust percentage and processing time results can be found in Appendix L, M, and N.

Table 7.6 Mean and SD of RP - 0.1% Template

Distance	Mean (%)	SD
10 ft	0.1047	0.0070
15 ft	0.0957	0.0073
30 ft	0.1644	0.0101
45 ft	24.0613	20.4627
60 ft	60.1043	11.6294
Note: SD (Standard Deviation), RP (Rust Percentage)		

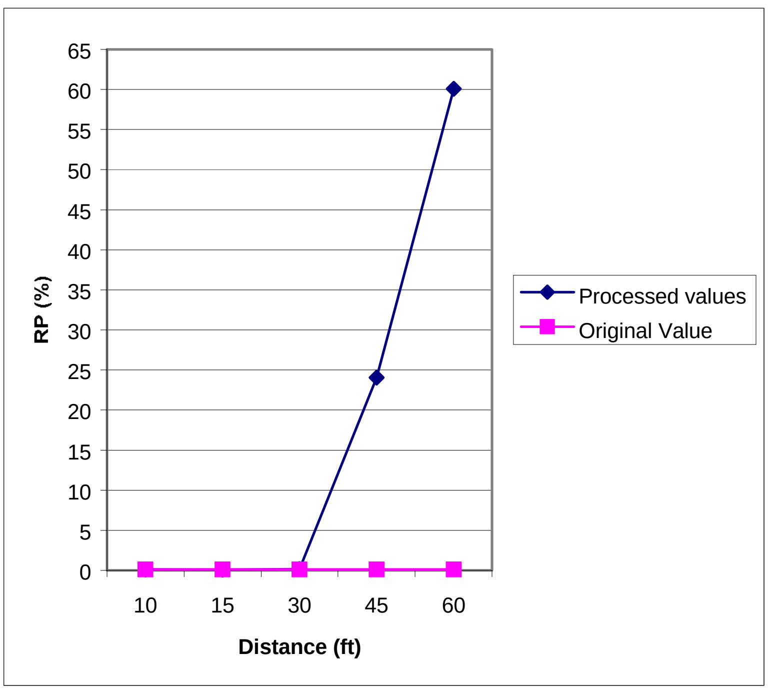


Figure 7.4 Rust Percentage Curve – 0.1% Template

Table 7.7 Mean and SD of RP - 0.3% Template

Distance	Mean (%)	SD
10 ft	0.2645	0.0137
15 ft	0.2508	0.0141
30 ft	0.4469	0.0253
45 ft	1.0664	0.1452
60 ft	3.9084	1.7233

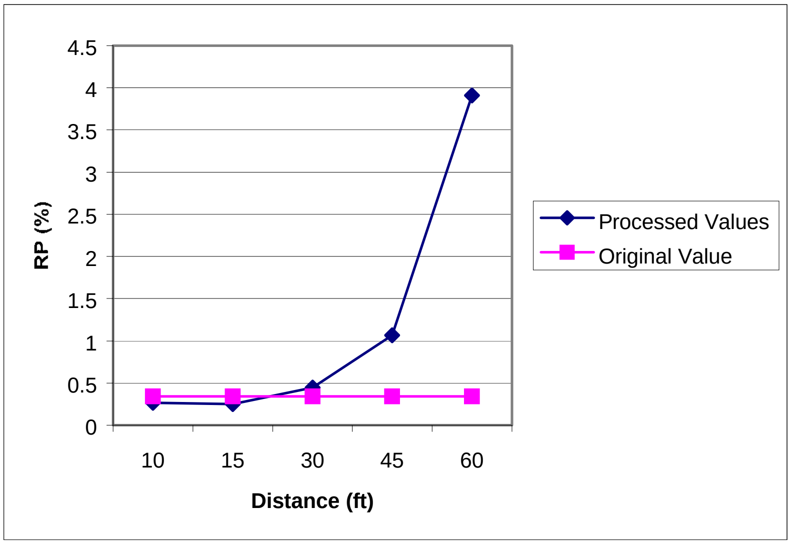


Figure 7.5 Rust Percentage Curve – 0.3% Template

Table 7.8 Mean and SD of RP - 1% Template

Distance	Mean (%)	SD
10 ft	0.9503	0.0370
15 ft	0.8660	0.0253
30 ft	0.8054	0.0310
45 ft	1.0519	0.0349
60 ft	1.7132	0.0815

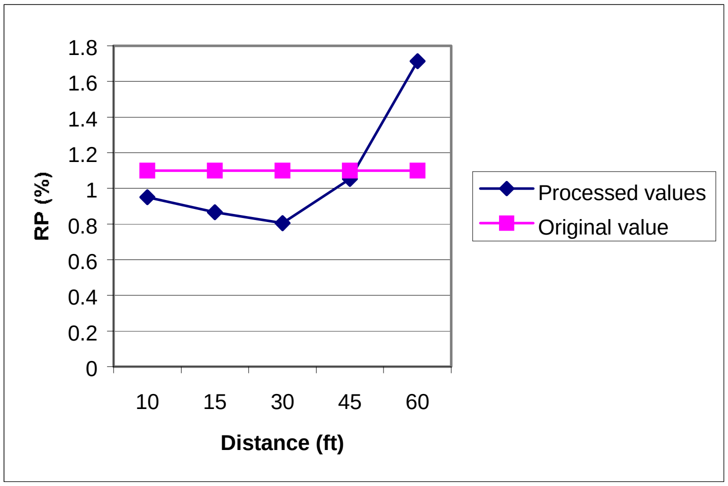


Figure 7.6 Rust Percentage Curve – 1% Template

7.4.3 Summary for objective (3)

The research findings can be summarized as follows:

(1) The all images were acquired at widely open playing fields near the campus on February 20, 2003 for 0.1% and 1% image templates and March 11, 2003 for 0.3% image template. Pre-planned enlarged ASTM template with 24 by 24 inches was installed on a net fence, and thirty images from each of the following different distances were taken. The selected distances are 10, 15, 30, 45, and 60 ft.

(2) The mean spot areas or rust percentages from different distances for 0.1% image template are: 0.1047% from 10 ft, 0.0957% from 15 ft, 0.1644% from 30 ft, 24.0613% from 45 ft, and 60.1043% from 60 ft. the rust percentage of 0.1% ASTM template was found to be 0.1373% from computer processing. The result of 0.1047% from 10 ft, therefore, is fairly close to the original value. The reason for the lower results may be due to the errors coming from image acquisition and image pre-processing. The mean rust percentage from 15 ft is slightly lower than that from 10 ft, and then the mean rust

percentages start to go up from 30 ft. But, the mean rust percentage from 30 ft is still close to the original value and has a fairly low standard deviation. On the contrary, the mean rust percentages from 45 ft and 60 ft sharply increase while producing unrealistic rust percentages and standard deviations. As image acquisition is performed from longer distances, the images become less clear. Indistinct images cause the image-processing program of SKMN to fail to produce accurate results.

(3) The mean spot areas or rust percentages from different distances for 0.3% image template are: 0.2645% from 10 ft, 0.2508% from 15 ft, 0.4469% from 30 ft, 1.0664% from 45 ft, and 3.9084% from 60 ft. the rust percentage of the 0.3% ASTM template was found to be 0.3387% from computer processing. The result of 0.2645% from 10 ft, therefore, is fairly close to the original value. The reason for the lower results may be due to the errors coming from image acquisition and image pre-processing. The mean rust percentage from 15 ft is slightly lower than that from 10 ft, and then the mean rust percentages start to increase for images taken beyond 30 ft. But, the mean rust percentage from 30 ft is still close to the original value and has a fairly low standard deviation. On the contrary, the mean rust percentages from 45 ft and 60 ft sharply increase while generating high rust percentages and standard deviations. As image acquisition is performed from longer distances, the images become less clear. Indistinct images cause the image-processing program of SKMN to fail to produce accurate results.

(4) The mean spot areas or rust percentages from different distances for 1% image template are: 0.9503% from 10 ft, 0.8660% from 15 ft, 0.8054% from 30 ft, 1.0519% from 45 ft, and 1.7132% from 60 ft. the rust percentage of 1% ASTM template was found to be 1.1063% from computer processing. The result of 0.9503% from 10 ft, therefore, is

fairly close to the original value. The reason for the lower results may be due to the errors coming from image acquisition and image pre-processing. The rust percentages slightly decrease as the distances increase up to 30 ft. But, rust percentages at 45 ft and 60 ft sharply increase leading to the opposite trend compared to the rust percentages at shorter distances. As image acquisition is performed from longer distances, taken images become less clear. Indistinct images cause the image-processing program of SKMN to fail to produce accurate results. From the processed images, SKMN method recognizes relatively small spots smaller than real spot sizes, and recognizes relatively large spots larger than real spot sizes.

(5) In short, the rust percentage curves from 10 ft to 30 ft for three kinds of rust images can be applied for rust percentage determination in the future. Correction factors for intermediate values should be prepared. The rust percentages after 30 ft are not likely to be realistic.

7.5 Summary of Chapter

This chapter described the further investigation on SKMN method in detail. SAC members set seven objectives for the investigation. The methodology and experiment results for objective (1), (2), and (3) of the 2nd extension study were explained in this chapter. From the experiment for objective (1) and (2), it was concluded that angles, distances, and cleanliness affect the results of rust percentage determination. In the experiment for objective (3), the rust percentage curves increased sharply after 30 ft for the three kinds of image templates, while producing unrealistic results. The results within 30 ft seem to be effective and can be applied for future study.

Table 7.9 shows the maximum allowable tolerances and rust percentages resulted from the Table 7.7. For example, if the stipulated acceptable criterion is 0.3 %, and the image is taken 10 ft away with 90^o angle under more than 10,000 lux, and the surface is clean, the maximum limit of error for 0.3 % is ± 0.0269 % on 95 % confidence level. If the obtained rust percentage is above 0.3269 %, the sampled image will be determined as a defect.

Table 7.9 Maximum Allowable Tolerances

Distance	SD	Max. SD		Max. Allowable %	
		α=0.05	α=0.01	α=0.05	α=0.01
10 ft	0.0137	0.0269	0.0353	0.3269	0.3353
15 ft	0.0141	0.0276	0.0363	0.3276	0.3363
30 ft	0.0253	0.0496	0.0653	0.3496	0.3653
Note: SD (Standard Deviation), α (Confidence level)					

Objective (4) was not pursued further because the infrared-imaging cameras are very expensive and optical devices cannot be mounted on the currently used camera. Indicated by the Flir systems, infrared-imaging cameras used for research and development range from $25,000 to $90,000. Moreover, checking with staff of Bestbuy and Circuit City stores in Lafayette, they pointed out that reflective lenses and optical devices cannot be mounted on the Kodak DC 280 digital camera that was previously purchased for this research.

Objective (5), (6), and (7) of the 2nd extension study that are related to the implementation procedures for bridge painting warranty applications are described in Chapter VIII, respectively.

CHAPTER VIII

IMPLEMENTATION PLANS

The objective (5), (6), and (7) of the 2nd extension study were addressing three areas. They are: warranty clauses, sampling plan and image processing. Warranty clauses are needed to assure the workmanship of bridge painting contractors and better preserve bridge coating quality. A sampling plan is necessary since the images of an entire bridge cannot be taken during a bridge inspection. Image processing encompasses the steps from image acquisition to determination of rust percentage.

8.1 Warranty Clauses

As illustrated in Chapter IV, the research regarding warranty clauses was performed by collecting some currently used steel bridge painting warranties from MDOT, IDOT, ODOT, INDOT pavement warranty, and INDOT 1999 proposed warranty. After conducting thorough analysis and consulting other issues on the critical parameters constituting a warranty contract with SAC members, the following table was recommended to INDOT for immediate implementation for the coming construction season. The full context of the warranty clause is prepared in Appendix B.

Table 8.1 Final Proposed Warranty Clauses

	Area of Comparison	INDOT Proposal (June 2003)
1	*Warranty Period*	Ratio from the paint expected lifetime under the existing environmental conditions of the area. Note: Five years for large-scale implementation.
2	*Defects Definition*	Six main categories of defects definition. Depends on thickness measurement, rust percentage, and final visual inspection. Contains references specifications from ASTM and SSPC for comparison purposes.
3	*Inspection Schedule*	During the month before the end of the specified warranty period, biannual regular inspection, or, at any time the bridge coating system requires immediate remedies. Notice: The Contractor should provide inspection equipment.
4	*Submittal of Repair Procedures and Progress Schedule*	To be submitted in writing within 10 working days of notice of defective areas.
5	*Season of Work*	All paint repair work should be done the same season as the inspection, unless the seasonal limitations of this specification prevent the completion that season. In this case, corrective work should be completed the following season. Notice: All additional defective areas that appear between the time of inspection and the actual corrective work being performed should also be repaired.
6	*Liability Insurance*	To be submitted to INDOT Contracting Department prior to any works.
7	*Traffic Control*	Traffic control and signing are the Contractor's responsibilities to supply for the period of corrective work. The Contractor's traffic control plan shall be submitted to the District Construction Engineer for approval before inspection is performed.
8	*Supplementary Performance Bond*	Prior to execution of the contract, and within 10 days of receiving Notice of Award, the successful Bidder shall furnish a contract performance bond and a payment bond, each to be in an amount equal to the Department's estimate. The Contractor shall also furnish a 5-year warranty maintenance bond equal to 50% of the total price as contracted. The value is subject to increasing if needed in the future.
9	*Supplementary Lien Bond*	
10	*Surety Company*	The Surety that underwrites the maintenance bond is required to have an A.M. best rating of "A-" or better.
11	*Work Permit*	Prior to proceeding with any warranty work or monitoring, a Miscellaneous Permit should be obtained from the Department.

8.2 Sampling Plan

Appropriate random sampling plan has to be prepared in order to get unbiased sample images during steel bridge coating inspection (Chang et al. 1999). The sampling plan is presented as follows.

1. Details of the bridge to be inspected: The numbers of beams and diaphragms should be known before the start of sampling procedure.

2. Coding: Steel beams and diaphragms are numbered according to their geographical direction starting at the top left corner. Figure 8.1 shows a coding example, where ‘WE’ indicates West-East, and ‘NS’ means North-South.

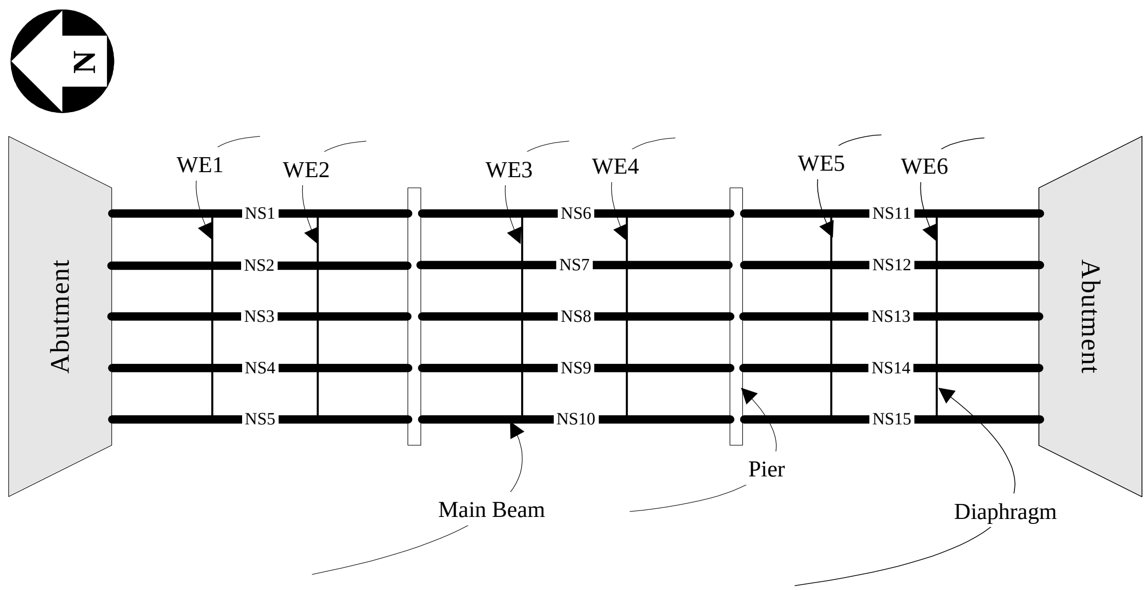


Figure 8.1 Statistical Plan Bridge Labeling Sequence (View I)

3. Sampling table: After the coding is finished, a detailed sampling table should be made for the convenience of random sampling. In the sampling table, all coded beams and diaphragms are numbered sequentially based on “sections”. In Figure 8.2, there are three sections in each beam and four sections in each diaphragm. The way of numbering sections also starts from the top left corner with diaphragms numbered after beams. In the picture, there are 15 beams and 6 diaphragms. Therefore, the numbers of beam sections start from 1 to 45, and the numbers of diaphragm sections are from 46 to 69 as shown in

Table 8.2. To make a more accurate sampling table, users can number both sides of each section and thus the total number will be doubled.

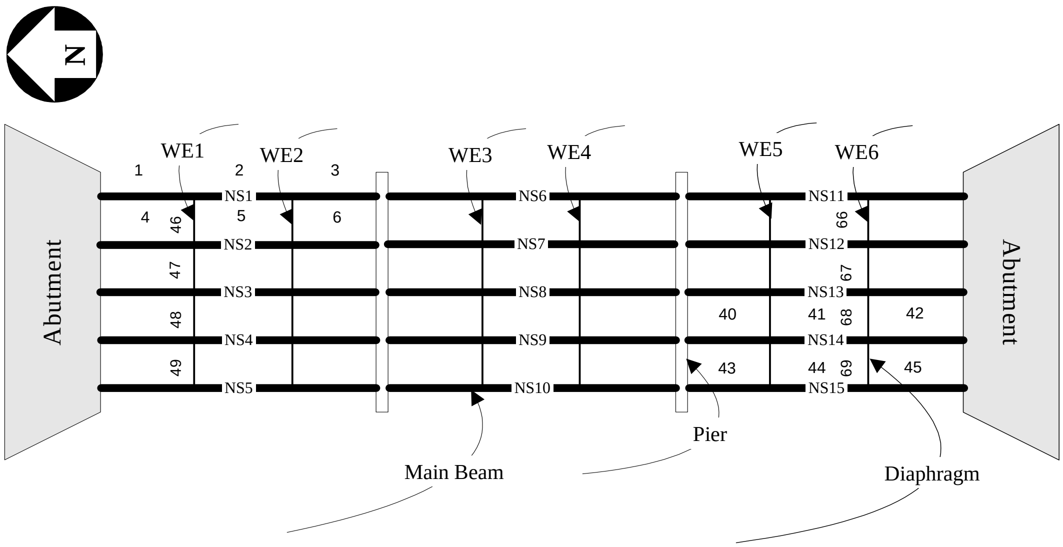


Figure 8.2 Statistical Plan Bridge Labeling Sequence (View II)

Table 8.2 Sampling Table

Number	***Beam***	***Number***	***Diaphragm***
1	NS1	46	WE1
2	NS1	47	WE1
3	NS1	48	WE1
4	NS2	49	WE1
5	NS2	50	WE2
⋮	⋮	⋮	⋮
42	NS14	66	WE6
43	NS15	67	WE6
44	NS15	68	WE6
45	NS15	69	WE6

4. Sampling plan: The double sampling plan is recommended for acceptance assessment. First, take 10 samples and count the number of defects. If the defect number is 0 or 1, the painting work of the bridge is accepted. If the defect number is equal to or larger than 3, the painting work is rejected. If the defect number is equal to 2, a second set of 10 samples should be taken. In the second set of samples, if the defect number is 0, 1, or 2, the painting work is accepted. If the defect number is equal to or larger than 3, the painting work is rejected.

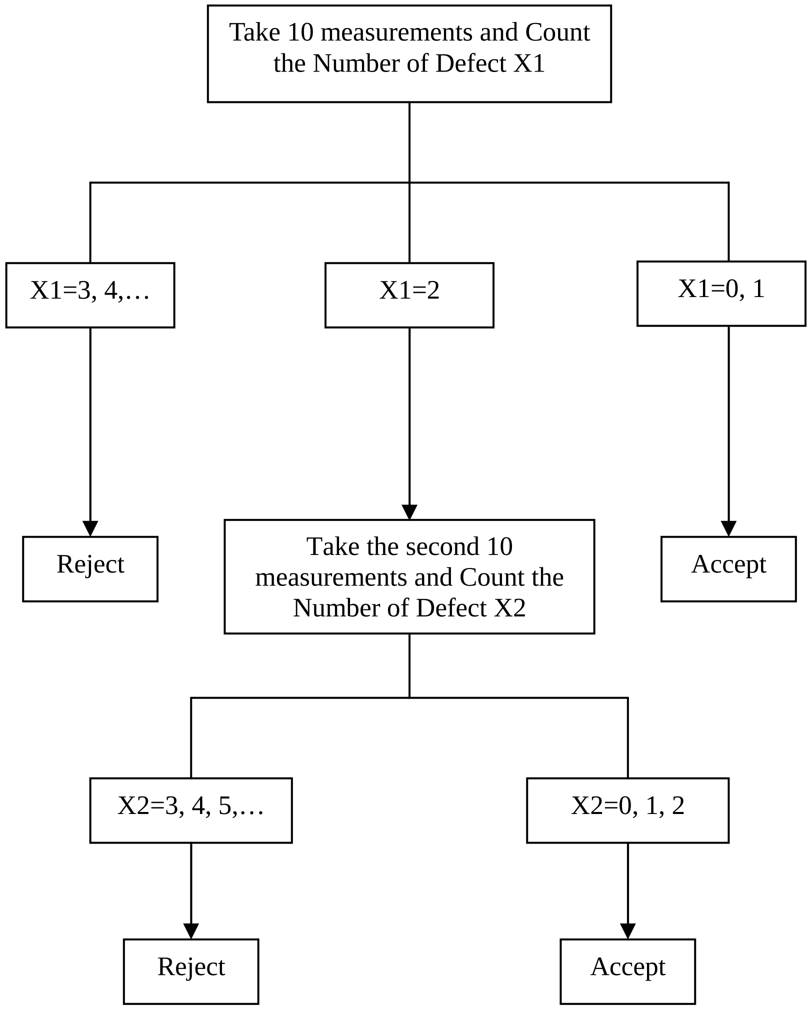


Figure 8.3 Double Sampling Plan

When taking 10 samples, the number of samples between bridge components has to be determined for unbiased sampling. For instance, selecting 10 images only from beams may not produce objective and reliable results. For unbiased sampling bridge elements from beams and diaphragms can be categorized as shown in Table 8.3. In this example, the total number of beams is 45, and the total number of diaphragms is 24, so the ratio of beams to diaphragms is 0.65:0.35. Therefore, the sampling plan that 6 samples are taken from beams and 4 samples are taken from diaphragms can be prepared.

Table 8.3 Categorization of Bridge Elements

Category	Elements	Total
C1 (Beam)	NS1, NS1, NS1, NS2, NS2… NS15, NS15, NS15	45
C2 (Diaphragm)	WE1, WE1, WE1, WE1…WE6, WE6, WE6, WE6	24

5. Random sampling: The random number generator is used for random sampling. It evenly generates random numbers between 0 and 1. (A random number could be 0 but has to be less than 1.) A random number could be converted to a section number by the following equation:

Section Number = [Random Number * 100 * (N/100)] = [Random Number * N]

Where [] is a rounding operator, and N indicates the total number of each bridge component.

For example, in the beam case, N is equal to 45. Let's assume a random number was selected to be 0.5. And then, selection number is as follows.

*Section Number = [0.5 * 100 * (45 / 100)] = [22.5] = 23*

The 23rd element is selected from the above calculation.

The first set of 6 samples can be selected by taking the first 6 different section numbers generated by the random number generator. If a second set is required, it can be generated with the same way. After the section numbers are determined, images will be taken with a digital camera or a camcorder.

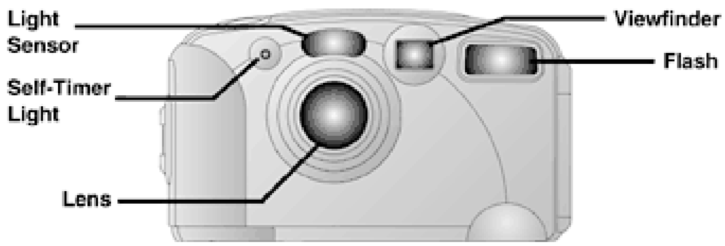
8.3 Image Processing Procedure

8.3.1 Step-by-step procedure for digital camera

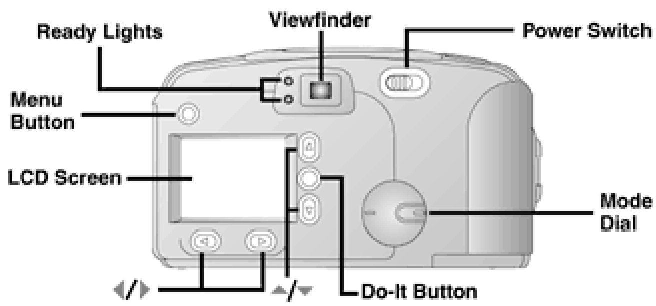
This part describes the development of a step-by-step procedure to use a digital camera for capturing the steel bridge paint images. In this research project, KODAK DC 280 zoom digital camera was used for image acquisition (see Figure 8.4).

Figure 8.4 KODAK DC 280 Digital Camera

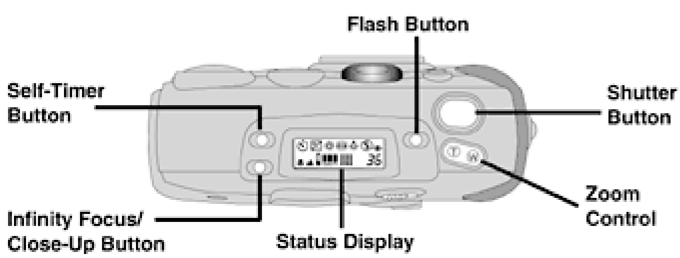
The instructions about how to take images and transfer taken images to a personal computer are explained as follows. And, the main control parts of the digital camera are shown for easy understanding in Figure 8.5.



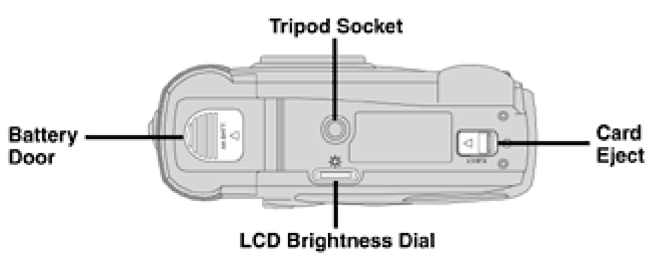
Front side view



Back side view



Top side view



Bottom side view

Figure 8.5 Main Control Parts of Digital Camera

1. Image acquisition

- To take still images

(1) Set the Mode dial to Capture.

(2) Slide the Power switch to the right to turn on the camera.

(3) Center the subject using the guide marks in the Viewfinder.

(4) Press the Zoom control if necessary. When you look through the Viewfinder, the subject appears closer as you press the T Zoom button, and farther away as you press the W Zoom button.

(5) Press the Shutter button half-way down to lock in the camera auto focus.

(6) Press the Shutter button completely down to take the picture.

- To review the pictures taken.

(1) Set the Mode dial to Capture.

(2) Slide the Power switch to the right to turn on the camera.

(3) Set the Mode dial to Review. The LCD displays the last picture taken with the frame number.

(4) Use the ◀ / ▶ buttons to scroll through and view the pictures on the LCD.

(5) Press the Menu button to display the filmstrip and the main Review screen. The Review Menu icons, filmstrip, and memory bar appear over the current picture.

(6) Use the ◀ / ▶ buttons to scroll through the filmstrip. The memory bar indicates the amount of space on the camera memory card. The dark section represents the portion of the card that is filled.

(7) To exit, press the Menu button.

- To delete one or all of your pictures

(1) Set the Mode dial to Capture.

(2) Slide the Power switch to the right to turn on the camera.

(3) Set the Mode dial to Review.

(4) Press a ◄ / ► button until you find a picture you want to delete.

(5) Press a Menu button.

(6) Operate a ▲/▼ button until a  icon is highlighted.

(7) Press a Do-it button. The Delete screen appears.

(8) Press a ▲/▼ button until Picture or All pictures are highlighted.

(9) Press the Do-it button. The picture is permanently deleted from the camera memory card.

(10) To exit Delete, highlight Exit, then press the Do-it button.

2. Image transfer to a computer

- Software installation

To open and download images stored at the camera memory card the software supplied with Kodak shall be installed on your computer first. To install the software:

(1) Close all other software programs before starting the installation CD.

(2) Place the installation CD into the CD-ROM drive.

(3) Load the software.

(4) Follow the on-screen instructions to install the software.

(5) If prompted, restart the computer when the software installation is complete.

- Connecting to a computer using a serial or USB cable

(1) Set the Mode dial to Capture.

(2) Slide the Power switch to the right to turn on the camera.

(3) Set the Mode dial to Connect.

(4) Plug the appropriate end of the serial cable into an available 9-pin serial port on the computer (see Figure 8.6). Serial ports are usually labeled COM1 and COM2. If you have USB cable, plug the appropriate end of USB cable into the port on the computer with the USB symbol.

(5) Open the serial/USB port door on the side of the camera.

(6) Plug the other end of the serial cable into the camera serial port.

(7) Slide the Power switch to the right to turn on the camera.

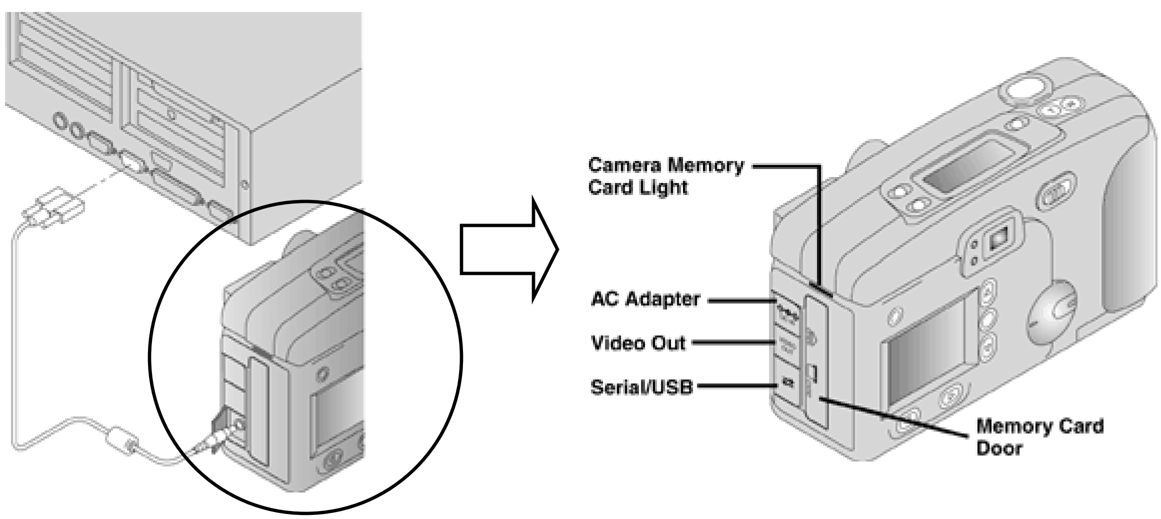


Figure 8.6 Serial Cable Connection

- Starting the Kodak software to manage picture files

With the camera connected to your computer, you are now ready to open and use the software that you installed.

(1) Double-click on the My Computer icon on your computer. The My Computer window appears.

(2) Double-click on the Camera icon. The My Computer window appears listing individual files.

(3) Double-click on the DCIM file.

(4) Double-click on the 100DC280 file. All picture files taken appear.

(5) You can transfer the taken images to another folders you want to move to by just clicking and dragging.

8.3.2 Step-by-step procedure for digital camcorder

A digital camcorder can be also used for capturing rusted images. The way to operate it is very similar with a digital camera. For image acquisition, SONY Digital 8 DCR-TRV720 camcorder was used. The main control parts are shown in Figure 8.7.

1. Image acquisition - How to record still images using a digital camcorder

- To insert “Memory Stick” supplied with the camcorder.

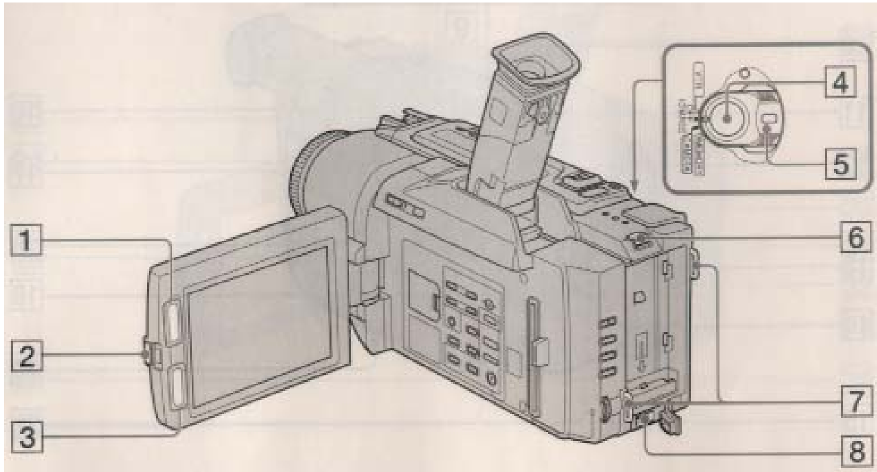
(1) Open the lid of the cassette compartment.

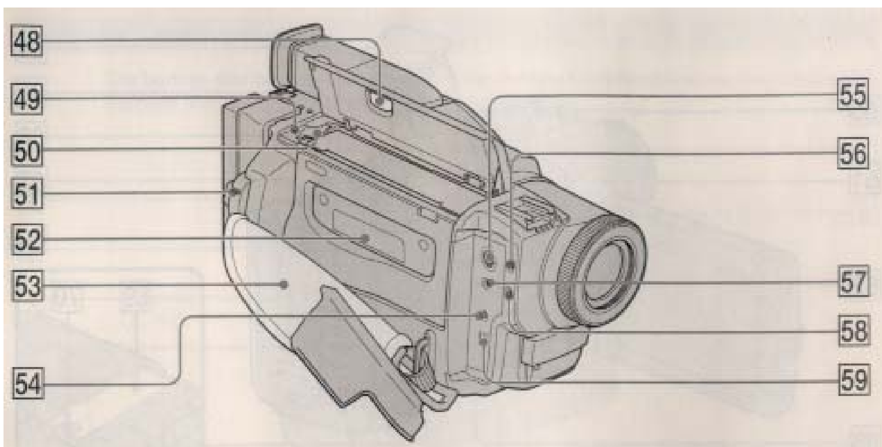
(2) Insert the “Memory Stick” with the ▲ mark facing toward the “Memory Stick” compartment until it clicks.

(3) Close the lid of the cassette compartment.

- To record still images.

(8) Set the POWER switch to MEMORY. Make sure that the LOCK is set to the right (unlock) position.





1. LCD BRIGHT buttons	2. OPEN button
3. VOLUME buttons	4. START/STOP button
5. POWER switch	6. BATT RELEASE lever
7. Hooks for shoulder strap	8. DC IN jack
48. EJECT button	49. Access lamp
50. “Memory Stick” compartment	51. LOCK knob
52. Cassette compartment	53. Grip strap
54. LANC/DIGITAL I/O jack	55. S VIDEO ID-2 jack
56. Headphone jack	57. AUDIO/VIDEO ID-2 jack
58. MIC (PLUG IN POWER) jack	59. DV IN/OUT jack

Figure 8.7 Main Control Parts of Digital Camcorder

(9) Keep pressing PHOTO lightly. The green ● mark stops flashing, then lights up. The brightness of the image and focus are adjusted, being targeted for the middle of the image and are fixed. Yet recording does not start. (When you record pictures, you can use a LCD screen or a viewfinder. If you choose the LCD screen, the viewfinder turns off automatically, and vice versa.)

(10) Press PHOTO deeper. The image displayed on the screen will be recorded on the “Memory Stick”. Recording is complete when the bar scroll indicator on the screen disappears. (The taken images are stored in a ‘JPG’ format.)

2. Image Transfer to Computer

- Application software (PictureGear 4.1 Lite supplied with the camcorder) and a PC serial cable supplied with the camcorder required for this operation
- Install the application software to your computer.
- Connect the camcorder and the computer using a serial cable. Beside the cassette compartment, there is a small cover. If you open it, you can see many input jacks. Among them, plug in the LANC/DIGITAL I/O (See Part 54 in Figure 8.7). The other part is connected to the serial port on your computer.
- Open the software and download the images. (Path to download: Click ‘File’ → Go to ‘Connect to device’ → Click ‘Video camera’, Figure 8.8 shows the downloaded images)
- Click the images that you want to select. (If you want to select several images, apply the ‘Shift + Arrow keys’ properly. Figure 8.9 shows the selected images that are indicated with light green color.)
- Click the right button of mouse and choose ‘Copy’. And then, downloading

images is started.

- Go to the directory you want the images to be stored and Click ‘Paste’.

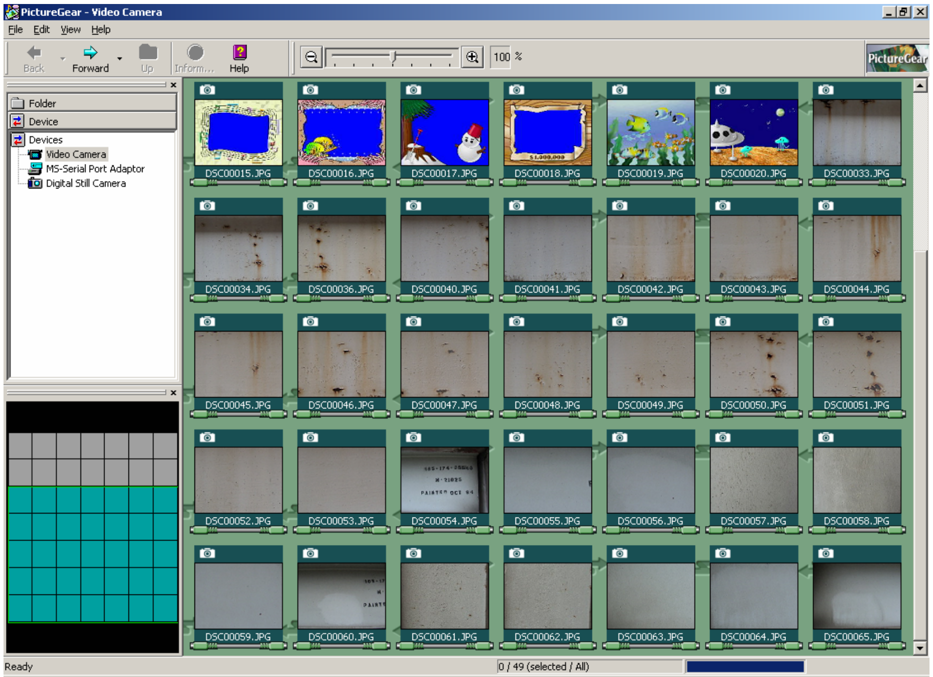


Figure 8.8 Downloaded Images from Digital Camcorder

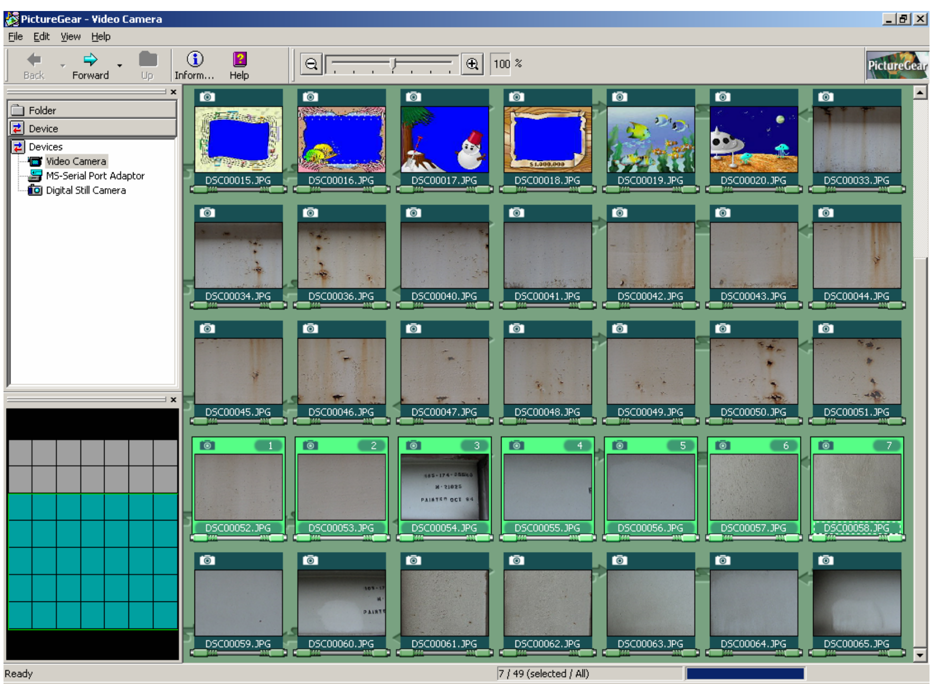


Figure 8.9 Selected Images

8.3.3 Application of software for rust percentage calculation

After taking steel bridge paint images and transferring the images to a computer, the images can be processed using SKMN method running on the MATLAB software.

1. Preparation to use application software

- Application software of MATLAB required for image processing (MATLAB v5.3 is used in this case.)
- Open the attached file named as ‘SKMN’ that is a MATLAB file to process rust images and calculate rust percentages.
- Locate the SKMN file to your main directory in the MATLAB program. (1) Open the MATLAB software. (Figure 8.10 shows the initial screen of MATLAB.)

  (2) Do ‘Set path’ task to let the MATLAB know where your NFRA file is located. (Path to ‘Set path’: Click ‘File’ → Click ‘Set path’ → browse your file → (After finding your file) Click ‘OK’ → Click ‘File’ → Click ‘Exit path browser’)
- Open the given file named as ‘SKMN’ that is a MATLAB program file to process rust images and calculate rust percentages.
- Type the file name you want to process. (Refer to Figure 8.12.)

2. Running the program

- Run the program of ‘SKMN’ at the command window (Path to run: type ‘SKMN’ → hit ‘Enter’, Refer to Figure 8.11.)

- A binary processed image and a rust percentage are obtained after tens of seconds (Refer to Figure 8.13.)

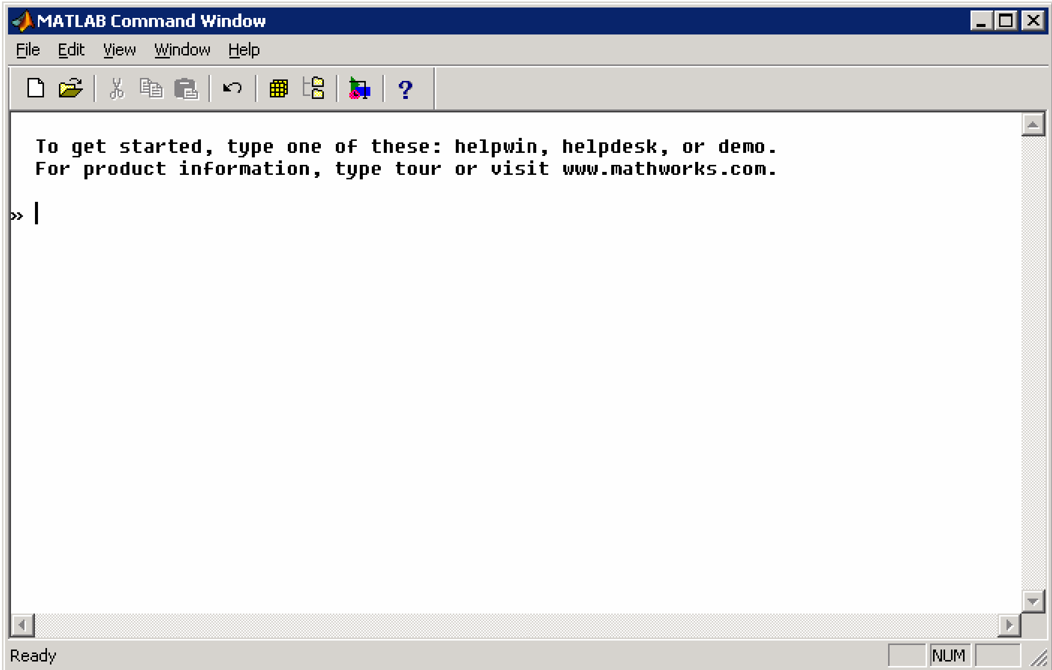


Figure 8.10 MATLAB Initial Screen

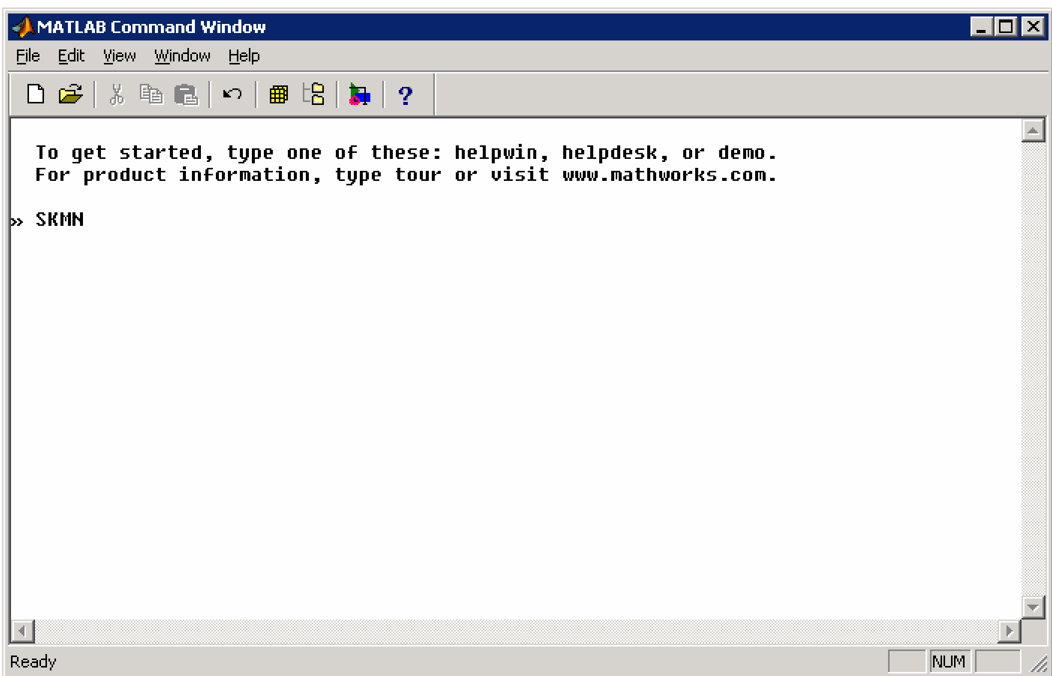


Figure 8.11 Typing ‘SKMN’ Command

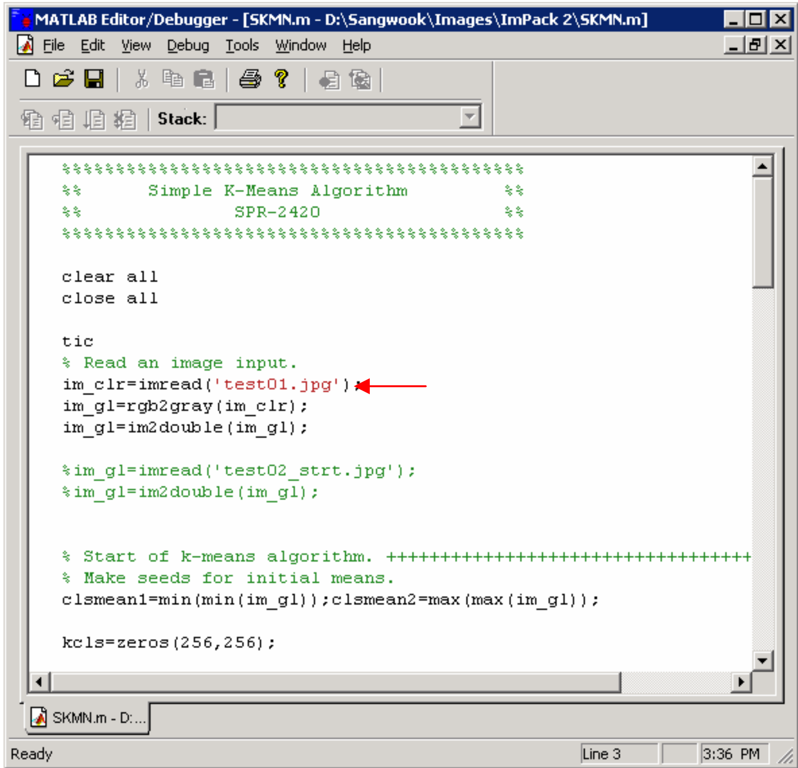


Figure 8.12 Typing File Name to Process Rust Image

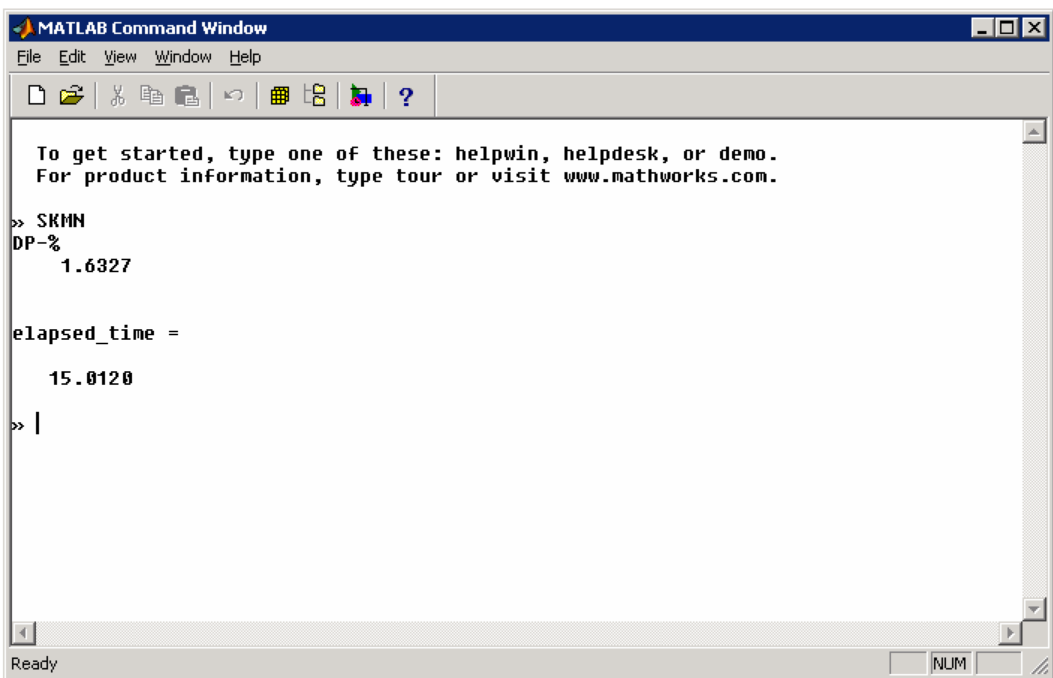


Figure 8.13 Calculated Rust Percentage and Time

CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

INDOT is faced with the continual challenge of better preserving its bridge infrastructure systems. To enhance the bridge coating quality, along with the limited annual budgets for the statewide maintenance activity, further examination of applying warranty clauses in painting projects is needed. The introduction of warranties will allow INDOT to hold contractors responsible for the quality of materials and workmanship used in the project.

The researchers under the direction of Study Advisory Committee (SAC) members conducted a thorough study for the establishment and implementation of contract warranties in bridge painting practices for INDOT. Recommended bridge painting warranty clauses were prepared for facilitating pragmatic implementation.

For the warranty clause development, an extensive literature review was performed and many currently used steel bridge painting warranties were analyzed and compared. Eleven major categories highlighted as paramount in establishing successful warranty clauses are the warranty period, defects definition, inspection schedule, repair procedure and progress schedule for correction work, season of work, liability insurance, traffic control, supplementary performance bond, supplementary lien bond, surety company, and work permit. After the comparison of other DOTs' warranty clauses and INDOT's bituminous warranty clause and discussions with SAC members, implementable bridge painting warranty clauses were developed for the specific use of

INDOT as shown in Appendix B.

A number of ASTM and SSPC standards provide a systematic procedure for identifying the bridge coating defects that may arise during the warranty period, including, rusting, blistering, cracking, and so forth. The various standards require human experts to refer to photographic templates in order to evaluate the relative percentages of rust. As visually quantifying the degree of rust percentages can be very difficult, even for a well-trained expert, the evaluation credibility would become questionable. However, computerized image processing techniques can supplement the weaknesses of traditional methods.

To assure the consistency and objectivity of steel bridge painting rust inspection and minimize potential disputes between INDOT and bridge-coating contractors, digital image processing techniques were developed in this project. A Neuro-Fuzzy Recognition Approach (NFRA) for the nondestructive quality assessment of steel bridge coatings was developed to enhance the warranty implementation practices. It utilizes various image processing techniques including K-means algorithm and segmentation and neuro-fuzzy sets as tools for visual data analysis, recognition, and classification. However, from the comparisons under the different conditions: brightness, angle, distance, and cleanness, Simplified K-Means Algorithm (SKMN) method demonstrated comparatively better performance than others as shown in the 1st extension study. Thus, SKMN method was further investigated through the 2nd extension study and recommended for demonstration projects.

9.2 Limitations

In general, the developed Simplified K-Means Algorithm (SKMN) method produces fairly effective recognition results on sharp contrast rust images. However, the SKMN approach may not perform well on indistinct contrast rust images. In other words, the performance of the SKMN approach may not be good on images whose defect color (or object color) and background color are similar. To process an indistinct contrast image, a pre-processing technique, such as filtering or contrast enhancement, may need to be applied to the images before the use of the SKMN approach.

Before taking images on the steel surfaces, cleaning work needs to be performed to generate more accurate results. As shown in the 1st extension study, the materials on the surfaces such as dirt, grease, soil, and so forth, can interfere with reliable image processing.

9.3 Recommendations for Future Work

The research contributed to the development of warranty clauses and the exploration of computerized percent rust recognition. Despite the many findings of this report, some recommendations for future work can be listed as follows:

9.3.1 Recommendations for warranty clauses

To fully make use of advantages of warranty contracts, an in-depth study may be required in the future to further understand the responsibilities between INDOT and contractor and to further develop the warranty clauses best suited to INDOT steel bridge painting projects. The follow-up study should address the following three issues.

♦ Conflict Resolution Team (CRT) may be necessary for the implementation of warranty clauses. Generally, CRT is required when warranty items have many possible causes of failures and are difficult to determine a correct cause. To enhance the effectiveness and creditability of CRT, the by-laws and organization structure need to be carefully framed in the future.

♦ Cost effectiveness of warranty contracts needs to be further researched in terms of warranty period. From the comparative study, warranty period varies from 2 to 5 years. It is not easy to determine the warranty period, while considering cost-effective solutions. INDOT also needs to continue monitoring the implementations, consider INDOT's situation, communicate with local contractors, and discuss with surety companies.

♦ Most states require proof of bond prior to construction works. From the comparative study, all DOTs demand bonding to contractors but the bond types and bond amount are various. The determination of bonding amount also requires more studies in the future.

9.3.2 Recommendations for image processing technique

The recommendations can be summarized as follows.

♦ The proposed Simplified K-Means Algorithm (SKMN) method, which was utilized for recognition of steel bridge rust images in this research, could be integrated with other bridge inspection packages, such as the infrared paint depth detection package. The integrated package may be further developed for real-time inspection use.

♦ For practical use, the paint images should be captured on a cleaned surface above 10,000 lux. The recommended maximum allowable tolerances of determining defect or non-defect are 0.3269%, 0.3276%, and 0.3496% for the distances of 10, 15, and 30 ft, respectively. If distances fall between, the tolerances can be prorated accordingly. After the defect is determined, the Double Sampling Plan can be used. If the defect number of the first 10 sample images is equal to or more than 3, painting work is rejected. If the defect number is 0 or 1, the work is accepted. If the defect number is 2, the second 10 samples have to be taken. If the defect number of second samples is 0, 1, or 2, then painting work is accepted. If the number is equal to or more than 3, the work is rejected.

♦ Most research efforts have been placed on binary recognition, which classifies an image to either the defect or the background. To make image processing more effective in construction applications, color image processing could be introduced in future research. It is expected to be able to overcome some limitations that existing image techniques like SKMN contain.

♦ Different colors of steel bridge paint could be experimented to discover the relationship between steel bridge paint colors and the corresponding recognition results.

♦ A more pragmatic sampling plan could be further studied in the way of minimizing the traffic disturbance and enhancing the safety while capturing the images.

♦ The digital camera used in this study generates quite reliable results within 30 ft range. However, it failed to recognize the rust beyond 30 ft. Seemingly, a more powerful digital camera could be purchased to further study on the images captured beyond 30 ft.

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Appendix A: INDOT Proposed Warranty Clause (January 1999)

INDIANA
DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISION
FOR
PERFORMANCE WARRANTY ON BRIDGE PAINTING

Performance Warranty

The Contractor shall unconditionally warrant to the Indiana Department of Transportation (INDOT) the paint system applied to the bridge to be free of defects, as hereinafter defined and determined by visual inspection and paint thickness measurements, for a period of two years from the date of the final inspection by the Engineer. On projects that extend over more than one year in contract duration, the warranty period shall be for two years from the project acceptance date.

The paint system will be considered defective if any of the following conditions are discovered within the two-year warranty period:

1. The occurrence of application-related failures including pinholes, holidays (incomplete coating), bleeding, blushing, or runs and sags.

2. Coating thickness less than the minimums specified in the painting specifications. The thickness will be considered satisfactory if and only if the average of the five spot measurements as specified by SSPC-PA 2 are within the specified thickness range, while single spot measurements are permitted to be 80% of the specified thickness.

3. Paint applied over dirt, debris, blasting debris, or rust products not removed during blast cleaning.

4. The occurrence of adhesion-related failures including undercutting, paint blistering, peeling, flaking, or scaling.

5. The occurrence of visible pinpoint rust or rust breakthrough in excess of 1% of the surface area of any painted structural element as specified by ASTM-D610.

6. Damage to the coating system caused by the Contractor while removing scaffolding or performing other work.

Warranty Evaluation

During the month of October before the end of the two year warranty period(s), or earlier if the Engineer finds a need to do so, the Engineer will inspect the bridge thoroughly for the paint system defects listed above. This inspection will be done by INDOT personnel using INDOT equipment. The Contractor will be notified in writing with the date of inspection. The Contractor may accompany the Engineer during inspection process. The Engineer will determine if there are defective areas present as defined above or not.

Acceptance by the Engineer of any portions of the work during the original contract cleaning and painting will not relieve the Contractor of the requirements of this warranty.

Corrective Work

All defective areas identified by the Engineer shall be repaired by the Contractor in accordance with the painting specifications. The repair procedures and progress schedule shall be submitted in writing within 10 working days of notice of defective areas to the Engineer for review and approval prior to any work. All paint repair work will be done the same season as the inspection, unless the seasonal limitations stated in the painting specifications prevents the completion that season. In this case, the corrective work will be completed the following season. The Engineer shall be given at least two weeks notification before the Contractor begins the corrective work and shall be allowed full inspection of all operations and provided safe access to the area being repaired.

The Contractor shall supply verification to INDOT prior to any work that the required liability insurance is in effect during the period the corrective work is being done.

When completing any identified corrective work, the Contractor shall comply with all regulations described in the original contract documents such as, but not limited to, the proper maintenance of traffic.

Warranty Bond

The Contractor shall furnish, upon completion of the original project works, a Warranty Bond to INDOT. The bond shall be in the sum of 20 percent of the original total contract amount. The bond is to secure the performance by the Contractor of correction work of any paint system defects that he is directed by INDOT to perform and all associated costs including payments for all labor, equipment, materials, etc. The Warranty Bond shall be in force for the period covering the two year warranty and the time required to perform any corrective work covered by the warranty. The Contractor shall use the form provided by INDOT, a copy of which is attached, and executed in accordance with the requirements of this special provision. The Warranty Bond must be properly executed by a surety company satisfactory and accepted to INDOT and be payable to the State of Indiana.

Upon completion of the work and final inspection of the project, the Warranty Bond shall become effective and shall continue in full force and effect until such time as INDOT advises the Contractor that there are either no paint system defects, or if the Contractor has been notified that there are paint system defects, and said paint system defects have been repaired by the Contractor to the satisfaction of the Engineer. The Engineer shall withhold in reserve an amount equal to 20 percent of the total contract amount until the Warranty Bond has been received.

Measurement and Payment

All costs associated with performance of the work, the required maintenance of traffic, and the required Warranty Bonds will not be paid for separately but will be considered to be included in the contractor's overhead and administrative costs.

INDIANA
DEPARTMENT OF TRANSPORTATION

WARRANTY
PAINT QUALITY

THIS WARRANTY, made by ____
(Contractor)

of ____

hereinafter called "Warrantor", in favor of the Indiana Department of Transportation, hereinafter called "Department";

WITNESSETH:

RECITALS:

1. The Department has contracted for the cleaning and painting structural steel on the ____ bridge on the ______________________________ Highway in _____________________ County, Indiana.
2. Under the provision of Contract No. ____________________________________ pertaining in part to painting of structural steel, entered into by ____ , and the
(Contractor)
Department in which ____
(Contractor)
is required to furnish the Department a written warranty for the paint system warranting against defects as stated in said contract for a period(s) of two years from the date(s) of final inspection by the Engineer, of ____ work under said contract.
(Contractor)

INDIANA
DEPARTMENT OF TRANSPORTATION

2 of 2
WARRANTY
PAINT QUALITY

NOW, THEREFORE, is consideration of the foregoing, warrantor hereby agrees and warranties that in every case in which any defect, as described in contract No. ____ occurs within said two year period(s), warrantor shall, forthwith upon receipt of written notice of such defect, repair said defective area.

It is expressly understood and agreed that the warranty and obligations herein set forth are made and undertaken by warrantor to and for the benefit for the Department.

IN WITNESS WHEREOF, _____________day of ___________ , 19____

____
(Contractor)

ATTEST: __________________________ BY: _______________________________

TITLE: ____________________________

INDIANA
DEPARTMENT OF TRANSPORTATION

SUPPLEMENTAL PERFORMANCE BOND

KNOW ALL MEN BY THESE PRESENTS, That we ______________________ as principal, and ____ as surety, a corporation duly organized and existing under and by virtue of the laws of the Sstate of __________________________ and duly authorized to transact the business of surety in the State of Indiana, are jointly and severely held and bound unto the Indiana Department of Transportation in the sum of _______________Dollars, for the payment for which we jointly and severely bind ourselves, our heirs and executors, administrators, successors and assigns firmly by these presents.

Whereas, the principal herein has, on the ______________day of _____________, 19___, made and entered into a certain agreement with the State of Indiana, by and through the Indiana Department of Transportation, which agreement is more fully described as ____ , Contract No. _______________________, under which agreement the principal agrees to furnish certain materials and to perform certain work which he agrees to do in accordance with the terms, conditions, and requirements as set out in said agreement, and whereas, in connection with said contract, the principal has executed a written warranty, a copy of which warranty is attached hereto and by this reference made a part thereof;

SUPPLEMENTAL PERFORMANCE BOND

AND, whereas, the principal has therein undertaken to warrant the work of cleaning and painting structural steel against any defects, as therein defined, for a period(s) of at least two years from the date(s) of final inspection of the project by the Engineer.

NOW, THEREFORE, THE CONDITION OF THIS BOND IS SUCH THAT if the principal herein shall faithfully and truly observe and comply with the terms of such warranty and shall well and truly perform all matters and things by him/her undertaken to be performed under said warranty upon the terms proposed therein and shall do all things required of said principal by the laws of this state and shall indemnify and save the harmless the State of Indiana and Indiana Department of Transportation against any direct or indirect damages of every kind and description that shall be suffered or claimed to be suffered in connection with or arising out of the performance of the said warranty by the Contractor or subcontractor, then this obligation is to be void, otherwise to remain in full force and effect.

In no event shall the obligations under this bond terminated without written consent of Indiana Department of Transportation.

Signed and sealed this ____________day of _______________ , 19___________ .

SURETY ______________________________ PRINCIPAL___________________________

BY ___________________________________ BY ___________________________________

Attorney-in-fact Official Capacity

Countersigned:

_________________________________ Attest: ____________________________________

Resident Agent Secretary

Appendix B: INDOT Proposed Warranty Clause (June 2003)

STATE OF INDIANA
DEPARTMENT OF TRANSPORTATION

SUPPLEMENTAL SPECIFICATION
FOR
PERFORMANCE WARRANTY ON BRIDGE PAINTING

<u>Performance Warranty</u>

The Contractor shall unconditionally warrant to the Indiana Department of Transportation (INDOT) the paint system applied to the bridge to be free of defects, as hereinafter defined and determined by thickness measurements, rust percentage, and final visual inspection of the applied paint system for the period of 5 years from the year of the final inspection by the Engineer. This inspection will be done by October of the last year of the warranty. On projects that extend over more than one year in contract duration, the warranty period shall be for 5 years from the year of the project acceptance.

The paint system will be considered defective if any of the following conditions are discovered within the 5-year warranty period.

1. The occurrence of application-related failures including pinholes, holidays (incomplete coating), bleeding, blushing, or runs and sags.

2. Paint applied over dirt, debris, blasting debris, or rust products not removed during blast cleaning.

3. Coating thickness less than the minimums specified in the painting specifications. The thickness will be considered satisfactory if and only if the average of the five spot measurements as specified by SSPC-PA 2 are within the specified thickness range, while single spot measurements are permitted to be 80% of the specified thickness.

4. Damage to the coating system caused by the Contractor while removing scaffolding, forms, or performing other work.

5. The occurrence of adhesion-related failures including undercutting, paint blistering, peeling, flaking, or scaling.

6. The occurrence of visible pinpoint rust or rust breakthrough in excess of 0.3% of the surface area of any painted structural element as specified by ASTM D610.

Exclusion to the warranty will be damage to the coating resulting from vehicle damage, fire, or other damage not caused by the Contractor or subcontractor.

Warranty Evaluation

During the month before the end of the specified warranty period or biannual regular inspection, or at any time the bridge coating system requires immediate remedies, the Engineer will inspect the bridge thoroughly for the paint system defects listed above. The inspection will be performed jointly by the INDOT personnel and the Contractor with equipment provided by the Contractor. The inspection equipment shall be OSHA approved, vehicle-mounted, and provide access to all areas of the structure. The Engineer will determine if there are defective areas present as defined above and define those areas.

Traffic control and required signing are the contractor's responsibilities to supply for the warranty evaluation inspection. The Contractor's traffic control plan shall be in accordance with as specified in the Department and/or as detailed in the plans, and shall be submitted to the District Construction Engineer for approval before inspection is performed.

Corrective Work

All defective areas identified by the Engineer at anytime during the warranty period shall be repaired by the Contractor in accordance with the painting specifications. The repair procedures and a progress schedule shall be submitted in writing within 10 working days of notice of defective areas to the Engineer for approval prior to any work. All paint repair work will be done the same season as the inspection, unless the seasonal limitations of the painting specifications prevent the completion that season. In this case, corrective work will be completed the following season. Any additional defective areas that appear between the time of inspection and the actual corrective work being performed will also be repaired. The Engineer shall be given at least two weeks notification before the Contractor begins the corrective work and shall be allowed full inspection of all operations and provided safe access to the area being repaired.

The Contractor shall submit the verification of liability insurance to the INDOT Contracting Department prior to any corrective works.

Traffic control and required signing are the Contractor's responsibilities to supply for the period of corrective work. The Contractor's traffic control plan shall be submitted to the District Construction Engineer for approval before the corrective work is performed.

Warranty Maintenance Bond

Prior to execution of the contract and within 10 days of receiving the Notice of Award, the successful Bidder shall furnish a contract performance bond and a payment bond, each to be in an amount equal to the Department's estimate. The Contractor shall also furnish a 5-year warranty maintenance bond equal to 50 percent of the total price as contracted. The value is subject to increasing if needed in the future.

The surety that underwrites the maintenance bond is required to have an A.M. best rating of “A-“ or better. The cost of the maintenance bond shall be included in the pay item.

The effective date of the maintenance bond is the date when the Department’s Form is issued for all paint items on the project. After the Form is issued, the Department will notify the Surety of the official start date for the warranty bond and the project will be finalized using standard procedures. The maintenance bond expires after 5 years from the issuance of the Form if no corrective work is required or after completion of the Contractor’s corrective work and approval by the Department.

The Contractor shall maintain the liability insurance as specified in the Department, covering any Contractor or Contractor authorized operations, persons, and equipment while any corrective work, or warranty evaluation review is being performed.

Measurement and Payment

All costs associated with performance of the work, the required maintenance of traffic, and the required warranty bond will not be paid for separately but will be considered to be included in the Contractor’s overhead and administrative costs.

Appendix C: IDOT, MDOT, and ODOT Warranty Clauses

State of Illinois
Department of Transportation

SPECIAL PROVISION
FOR
CLEANING AND PAINTING EXISTING STEEL STRUCTURES
COMPLETE REMOVAL (MODIFIED SSPC SP10) SURFACE PREPARATION

The Following Special Provision replaces Article 509.06 of Section 509 of the Standard Specifications.

Performance Warranty. The Contractor shall unconditionally warrant to the Department the paint system applied to the bridge to be free of defects, as hereinafter defined and determined by visual inspection and paint thickness measurements, for a period of 2 years from the date of final inspection by the Engineer. The warranty called for shall be on a warranty form furnished by the Department (attached). This warranty shall be submitted to the Engineer prior to the start of work.

The paint system will be considered defective if any of the following conditions are discovered within 2 year warranty period:

1. The occurrence of visible rust or rust breakthrough, paint blistering, peeling, or scaling.

2. Paint applied over dirt, debris, blasting debris, or rust products not removed during blast cleaning.

3. Incomplete coating or coating thickness less than the minimums specified in the painting specifications.

4. Damage to the coating system caused by the Contractor while removing scaffolding or performing other work.

The Engineer will inspect the bridge thoroughly for the paint system defects listed no later than the month before the end of the warranty period. The Contractor may accompany the Engineering during this inspection.

Acceptance by the Engineer of any portion of the work during the original contract cleaning and painting will not relieve the Contractor of the requirements of this warranty.

All defective areas identified by the Engineer shall be repaired by the Contractor. The repair procedures and Progress Schedule shall be submitted in writing within 10 working days of notice of defective areas to the Engineer for review and approval. All paint repair work will be done the same season as the inspection. The Engineer shall be given at least 2 weeks notification before the Contractor begins the corrective work and shall be allowed full inspection of all operations and provided safe access to the areas being repaired.

The Contractor shall supply verification to the Engineer that the required liability insurance is in effect during the period the corrective work is being done.

The Contractor shall furnish, in addition to the regular performance and lien bonds for the contract, a supplemental performance bond to the Department. The bond shall be in the sum of 15 percent of the original total contract amount. The bond is to secure the performance by the Contractor of correction work on any paint system defects that he/she is directed by the Engineer to perform and shall be in force for the period covering the two year warranty and the time required to perform any corrective work covered by the warranty. The Contractor shall use the form provided by the Department, a copy of which is attached, and executed in accordance with the requirements of this special provision.

Upon completion of the work and final inspection of the project, the supplemental performance bond shall become effective and shall continue in full force and effect until such time as the Department advises the Contractor that there are either no paint system defects, or if the Contractor has been notified that there are paint system defects, that the paint system defects have been repaired by the Contractor to the satisfaction of the Engineer. The Engineer will withhold in reserve an amount equal to 15 percent of the total contract amount until the Supplemental Performance Bond has been received.

All costs associated with performance of this warranty, the required maintenance of traffic, and the required supplemental performance bond, will not be paid for separately but will be considered to be included in the cost of Cleaning and Painting Existing Steel Structures.

MICHIGAN
DEPARTMENT OF TRANSPORTATION
BUREAU OF HIGHWAYS

Special Provision
for
Performance Warranty on Bridge Painting

Performance Warranty

The Contractor shall unconditionally warrant to the Michigan Department of Transportation (MDOT) the paint system applied to the bridge to be free of defects, as hereinafter defined and determined by visual inspection and paint thickness measurements, for a period of two years from the date of final inspection by the Engineer. On projects that extend over more than one year in contract duration, the Engineer may accept portions of the painting at the end of each annual work period and the warranty period shall be for two years from the acceptance date for each portion respectively. The warranty called for shall be on a warranty form furnished by the state, a copy of which is attached. This warranty shall be submitted to the MDOT Financial Services Division prior to the award of the contract.

The paint system will be considered defective if any of the following conditions are discovered within the two year warranty period:

1. The occurrence of visible rust or rust breakthrough, paint blistering, peeling, or scaling.

2. Paint applied over dirt, debris, blasting debris, or rust products not removed during blast cleaning.

3. Incomplete coating or coating thickness less than the minimums specified in the painting specifications.

4. Damage to the coating system caused by the Contractor while removing scaffolding or performing other work.

Warranty Evaluation

During the month before the end of the two end warranty period(s), or earlier, the Engineer will inspect the bridge thoroughly for the paint system defects listed. This inspection will be done using Department maintenance personnel and equipment. The Contractor may accompany the Engineer during this inspection. The Engineer will determine if there are defective areas present as defined above.

Acceptance by the Engineer of any portion of the work during the original contract cleaning and painting will not relieve the Contractor of the requirements of this warranty.

Corrective Work

All defective areas identified by the Engineer shall be repaired by the Contractor in accordance with the painting specifications. The repair procedures and Progress Schedule shall be submitted in writing to the Engineer for review and approval prior to any work. All paint repair work will be done the same season as the inspection, unless the seasonal limitations stated in the painting specifications prevents the completion that season. In this case the corrective work will be completed the following season. The Engineer shall be given at least two weeks notification before the Contractor begins the corrective work and shall be allowed full inspection of all operations and provided safe access to the areas being repaired.

The Contractor shall supply verification to the MDOT Financial Services Division that the required liability insurance is in effect during the period the corrective work is being done.

Special Supplemental Performance and Lien Bonds

The Contractor shall furnish, in addition to the regular performance and lien bonds for the contract, a supplemental performance bond to the Department. The bond shall be in the sum of 15 percent of the original total contract amount. The bond is to secure the performance by the Contractor of correction work on any paint system defects that he/she is directed by the Department to perform and shall be in force for the period covering the two year warranty and the time required to perform any corrective work covered by the warranty. The Contractor shall use the form provided by the Department, a copy of which is attached, and executed in accordance with the requirements of this special provision. If corrective work is required the Contractor shall provide a supplemental lien bond (form provided by the department) that is in effect for the duration of the corrective work. The supplemental performance and lien bonds must be in all respects satisfactory and acceptable to the Department, executed by a surety company authorized to do business in the State of Michigan.

Upon completion of the work and final inspection of the project, the supplemental performance bond shall become effective and shall continue in full force and effect until such time as the Department will, in accordance with the Paint Quality Warranty, advise the Contractor that there are either no paint system defects, or if the Contractor has been notified that there are paint system defects, said paint system defects have been repaired by the Contractor to the satisfaction of the Department as specified under the Paint Quality Warranty. The Engineer shall withhold in reserve an amount equal to 15 percent of the total contract amount until the Supplemental Performance Bond has been received.

Measurement and Payment

All costs associated with performance of the work and the required maintenance traffic, described under the Performance Warranty on bridge painting and the required supplemental performance bond, will not be paid for separately but will be considered to be included in the Contractor's overhead and administrative costs.

MICHIGAN
DEPARTMENT OF TRANSPORTATION
BUREAU OF HIGHWAYS

SPECIAL PROVISION
FOR
PERFORMANCE WARRANTY ON BRIDGE PAINTING

C:GJB 07-18-94
APPR:C:PAL:EDW:7-19-24

Performance Warranty

The Contractor shall unconditionally warrant to the Michigan Department of Transportation (MDOT) the paint system applied to the bridge to be free of defects, as hereinafter defined and determined by visual inspection and paint thickness measurements, for a period of two years from the date of final inspection by the Engineer. On projects that extend over more than one year in contract duration, the warranty period shall be for two years from the project acceptance date. The warranty called for shall be on a warranty form furnished by MDOT, a copy of which is attached. This warranty shall be submitted to the MDOT Financial Services Division prior to the award of the contract.

The paint system will be considered defective if any of the following conditions are discovered within the two year warranty period:

1. The occurrence of visible rust or rust breakthrough, paint blistering, peeling, scaling, or unremoved slivers.

2. Paint applied over dirt, debris, blasting debris, or rust products not removed during blast cleaning.

3. Incomplete coating or coating thickness less than the minimums specified in the painting specifications.

4. Damage to the coating system caused by the Contractor while removing scaffolding or performing other work.

Warranty Evaluation

During the month before the end of the two year warranty period(s), or earlier, the Engineer will inspect the bridge thoroughly for the paint system defects listed. This inspection will be done by MDOT personnel using MDOT equipment. The Contractor may accompany the Engineer during this inspection. The Engineer will determine if there are defective areas present as defined above.

Acceptance by the Engineer of any portion of the work during the original contract cleaning and painting will not relieve the Contractor of the requirements of this warranty.

Corrective Work

All defective areas identified by the Engineer shall be repaired by the Contractor in accordance with the painting specifications. The repair procedures and Progress Schedule shall be submitted in writing to the Engineer for review and approval prior to any work. All paint repair work will be done the same season as the inspection, unless the seasonal limitations stated in the painting specifications prevents the completion that season. In this case the corrective work will be completed the following season. The Engineer shall be given at least two weeks notification before the Contractor begins the corrective work and shall be allowed full inspection of all operations and provided safe access to the areas being repaired.

The Contractor shall supply verification to the MDOT Financial Services Division that the required liability insurance is in effect during the period the corrective work is being done.

When completing any identified corrective work the Contractor shall maintain traffic as described in the original contract documents.

Special Supplemental Performance and Lien Bonds

The Contractor shall furnish, in addition to the regular performance and lien bonds for the contract, a supplemental performance bond to MDOT. The bond shall be in the sum of 20 percent of the original total contract amount for “Cleaning Existing Steel Structure (Type4)” & “Coating Existing Steel Structure (Type 4).” The bond is to secure the performance by the Contractor of correction work on any paint system defects that he is directed by MDOT to perform and shall be in force for the period covering the two year warranty and the time required to perform any corrective work covered by the warranty. The Contractor shall use the form provided by the MDOT, a copy of which is attached, and executed in accordance with the requirements of this special provision. If corrective work is required the Contractor shall provide a supplemental lien bond (form provided by MDOT) that is in effect for the duration of the corrective work. The supplemental performance and lien bonds must be in all respects satisfactory and acceptable to MDOT, executed by a surety company authorized to do business in the State of Michigan.

Upon completion of the work and final inspection of the project, the supplemental performance bond shall become effective and shall continue in full force and effect until such time as MDOT will, in accordance with the Paint Quality Warranty, advise the Contractor that there are either no paint system defects, or if the Contractor has been notified that there are paint system defects, said paint system defects have been repaired by the Contractor to the satisfaction of the MDOT as specified under the Paint Quality Warranty. The Engineer shall withhold in reserve an amount equal to 20 percent of the total contract amount for “Cleaning Existing Steel Structure (Type 4)” & “Coating Existing Steel Structure (Type 4)” until the Supplemental Performance Bond has been received.

Permit

If corrective work is required the contractor shall apply to the District Utility-Permits Engineer for a permit to work within MDOT right-of-way (Form 7705). The permit fee and an individual permit performance bond shall not be required. The permit insurance requirements, however, shall apply.

Measurement and Payment

All costs associated with performance of the work, the required maintaining traffic, the required supplemental performance and lien bonds, and the required permit insurance will not be paid for separately but will be considered to be included in the Contractor's overhead and administrative costs.

STATE OF OHIO
DEPARTMENT OF TRANSPORTATION

SUPPLEMENTAL SPECIFICATION 885

FIELD PAINTING OF EXISTING STEEL WITH WARRANTY

August 10, 1999

885.01 Description. This item shall consist of furnishing all necessary labor, materials, and equipment to clean and paint all existing steel surfaces, as specified herein, and also unconditionally warrant the paint system applied to the bridge to be free of defects as defined in section 885.03. Acceptance by the Engineer of any portion of the work during the original cleaning and painting will not relieve the Contractor of the requirements of the warranty.

885.02 Warranty Maintenance Bond. When the Contractor provides the Department with the performance and payment bonds specified in 103.05, the Contractor shall also furnish a 5-year warranty maintenance bond equal to 100 percent of the total price for each item "885 Surface Preparation of Existing Steel, With Warranty."

The Surety that underwrites the maintenance bond is required to have an A.M. best rating of "A-" or better. The cost of the maintenance bond shall be included in the pay item.

The effective date of the maintenance bond is the date the Department's Form C-85 is issued for all paint items on the project. After the C-85 is issued, the Department will notify the Surety of the official start date for the warranty bond and the project will be finalized using standard procedures. The maintenance bond expires after 5 years from the issuance of the C-85 if no corrective work is required or after completion of the Contractor's corrective work and approval by the Department.

The Contractor shall maintain the liability insurance specified in 107.14, covering any Contractor or Contractor authorized operations, persons, and equipment while any corrective work, or warranty evaluation review is being performed.

885.03 Warranty Item and Remedial Actions. The paint warranty items the Contractor is responsible for are listed below and will be determined by visual inspection, destructive inspection and paint thickness measurements of the applied paint system for the period of years as specified in 885.02 of this specification.

The paint system will be considered defective if any of the following conditions are discovered within the specified warranty period.

1. The occurrence of visible rust or rust breakthrough, paint blistering, peeling, scaling or un-removed slivers.

2. Paint applied over dirt, debris, blasting debris, or rust products not removed during blast cleaning.

3. Incomplete coating or coating thicknesses less than the minimums specified in the paint system specifications

4. Damage to the coating system caused by the Contractor while removing scaffolding, forms, or performing other work.

Exclusion to the warranty will be damage to the coating resulting from vehicle damage, fire, or other damage not caused by the Contractor or subcontractor.

885.04 Materials. A three coat paint system consisting of: Organic Zinc or Inorganic Zinc Prime Coat, Epoxy Intermediate Coat and a Urethane Finish Coat.

The Contractor shall select a coating system meeting the requirements of Supplemental Specification 910 entitled OZEU Structural Steel Paint. If the contractor elects to use an inorganic zinc primer, the inorganic zinc shall meet the requirements of 708.17. The

Intermediate and finish coats shall meet the requirements of Supplemental Specification 910 and all coats shall be from the same manufacturer. The approved list of coatings meeting this specification is on file at the Office of Materials Management. District Offices and on the internet at: http://www.dot.state.oh.us/testiab/applist/chem/chemindx.htm.

885.05 Quality Control Quality control will consist of the following items:

A. Contractor Quality Control Specialist. Before any work begins, the Contractor shall designate one individual on each project as a Quality Control Specialist (only one person per project will be necessary unless the Contractor is working at more than 3 sites simultaneously). In which case, it will be necessary to provide an additional Quality Control Specialist for each additional three (or portion of three) sites being painted simultaneously. This person will not be a Foreman or member of the Contractor's production staff (ie. he will not abrasive blast, paint, recover spent abrasives, etc.). He will not be involved in any other miscellaneous tasks (ie. mixing paint, running errands, running or working on equipment, etc.) while any production work is taking place. Documentation that personnel performing quality control related functions are qualified shall be submitted to the Engineer prior to allowing the Quality Control Specialist (QCS) to begin work. Documentation/verification shall be provided to the Engineer that the QCS has received formal training from one of the following: KTA Tator, S. G. Pinney, or Corrosion Control Consultants. He shall be equipped with material safety data sheets, product data sheets, tools and equipment to provide quality control on all facets of the work and shall have a thorough understanding of the plans and specifications pertaining to this project. He shall be responsible for inspecting the equipment at the specified intervals, the abrasives, and the work, at all quality control points. He shall also be responsible for verifying that all work is done within the specified work limitations. He shall cooperate with the Inspector and compare and document quality control readings. He shall have the authority to stop work and the responsibility to inform the Contractor's Foreman of nonconforming work.

B. Quality Control Points. Quality control points (QCP) are points in time when one phase of the work is complete and ready for inspection by both the Contractor and the Engineer prior to continuing with the next operational step. At these points: The Contractor shall afford access to inspect all affected surfaces. If inspection indicates a deficiency, that phase of the work shall be corrected in accordance with these specifications prior to beginning the next phase of work. Discovery of defective work or material after a Quality Control Point is past or failure of the final product before final acceptance, shall not in any way prevent rejection or obligate the State of Ohio to final acceptance.

Quality Control Points (QCP)	PURPOSE
1. Solvent Cleaning	Remove asphaltic cement, oil, grease, salt, dirt, etc. followed by washdown
2. Grinding Flange Edges	Remove sharp corners,
3. Containment/Waste Disposal	Contain, collect & dispose of abrasive blasting debris
4. Abrasive Blasting	Blasted surface to receive paint
5. Prime Coat Application	Check surface cleanliness; apply prime coat; check coating thickness
6. Removing Fins, Tears, slivers	Remove surface defects and slivers
7. Caulking	Caulk areas
8. Intermediate Coat Application	Check surface cleanliness; apply intermediate coat, check coating thickness
9. Finish Coat Application	Check surface cleanliness, apply finish coat, check coating thickness
10. Final Review	Visual inspection of system for Acceptance and check total system thickness.

885.06 Surface Preparation. This item shall also consist of solvent cleaning, grinding flange edges, abrasive blasting, and providing a wash facility for the Engineer and Inspectors.

A. Solvent Cleaning (QCP #1). All traces of asphaltic cement, oil, grease, diesel fuel deposits, and other soluble contaminants, shall be removed by solvent cleaning (QCP #1) (see SSPC-SP 1 Solvent Cleaning for recommended practices). Under no circumstances shall any abrasive blasting be done to areas with asphaltic cement, oil, grease, or diesel fuel deposits. All solvent cleaned areas shall be subsequently washed before abrasive blasting as detailed below.

Washing shall be accomplished with potable water having a nozzle pressure of at least 1,000 PSI (7 Mpa) and a delivery rate of not less than 4 gallon (15 L) per minute. The Contractor, shall provide equipment specifications to verify the above. The equipment shall also be equipped with gauges to verify the pressure. The nozzle shall be held at a maximum of 12 inches (300 mm) from the surface being washed.

B. Grinding Flange Edges (QCP #2). All exposed bottom flange edges of longitudinal rolled and welded beams shall be rounded to a radius of 1/8 inch plus or minus 1/16 inch (3 mm plus or minus 1.5 mm) before abrasive blasting. This work may be done without weather and temperature restrictions. This work is included with surface preparation for payment.

C. Containment/Waste Disposal (QCP #3). Waste material generated by abrasive blasting operations is a solid waste and shall be handled as follows:
(1) Contained, (2) Collected, (3) Stored, (4) Evaluated, (5) Properly disposed.

All equipment shall be parked on ground covers free of cuts, tears or holes to prevent contamination of pavement or soil and to protect area under and around equipment.

The Contractor shall erect an enclosure to completely surround (around and under) the blasting operations to prevent the escape of dust and abrasive blasting debris. The ground cannot be used as the bottom of the enclosure unless completely covered with plastic or tarps.

The enclosure shall be constructed of flexible materials such as tarpaulins or containment screens (specifically designed for this purpose), or of rigid materials such as plywood. All materials shall be maintained free of tears, cuts or holes. All seams shall be overlapped a minimum of 6 inches (150 mm) and fastened together at 12 inch (300 mm) centers, or fastened and overlapped in a manner that insures a seal which does not allow openings between the screens in the containment. The vertical sides of the enclosure shall extend completely up to the bottom of the deck on a steel beam bridge. All blasting operations on a truss type bridge shall be completely enclosed, including top side. Bulkheads shall be used between beams to enclose the blasting area.

Vacuum blasting may be used in lieu of containment, providing that the vacuum blasting equipment is manufactured and marketed for this purpose and is equipped with controls which automatically shut down the blasting operation if the blast head brushes are not held in contact with the surface being cleaned.

All debris collected by these operations, removed from equipment or filters, or that has fallen to the ground, shall be collected and stored at the bridge site, if practical, for testing, evaluation and disposal. If not practical, an alternate location shall be mutually agreed upon by the Engineer and Contractor. Additionally, centralized cleaning stations for recyclable steel, ferric oxide, or aluminum oxide grit (if used) shall be set up at a location mutually agreed upon by the Contractor and Engineer. Storage shall be in steel containers and shall have lids which shall be locked at the end of each workday.

The Contractor shall obtain the services of a testing laboratory to obtain directly from the project site and evaluate a composite representative sample of the abrasive blasting debris for each bridge site. The person taking the sample will be an employee of the testing laboratory.

The composite sample shall consist of individual samples taken from all containers which are on the site at the time of the sampling. These individual samples shall be blended together to comprise one composite sample. The individual samples shall be of equal size. There shall be one individual sample taken from each drum and four randomly spaced individual samples taken from each container other than drums.

The individual samples shall be taken with stainless steel tools and placed into either clean glass or plastic containers.

All sampling shall be done in the presence of the Engineer. In addition to the above mentioned requirements, the sampling shall also comply with the requirements of U.S. EPA Publication SW 846.

A Chain of Custody must also accompany all composite samples. Included in this document shall be in the name. of the person taking the sample, the Company for which he works, the date and time which the sample was taken, the bridge from which it was taken, the Township and Municipality where the bridge is located and signatures of all persons involved in the Chain of Custody, including dates of possession.

The sampling shall be done within the first week of production blasting at each bridge. If the sampling is not done within the time allotted above, all blasting and painting operations on the bridge from which waste was generated, shall promptly cease.

The composite sample shall be tested for lead and chromium in accordance with U.S. EPA Publication SW 846. The test results and Chain of Custody records shall immediately be forwarded to the Director. If the material is hazardous, the Contractor shall also forward the names of the hauler and treatment facility to the Director. Any additional testing required by the hauler, treatment facility, or landfill will be paid for by Contractor.

All federal, state and local environmental protection laws, regulations and ordinances including, but not limited to, air quality, waste containment and waste removal must be observed during the performance of this contract.

In respect to enforcement of the above mentioned laws, bidders are advised that various governmental bodies have this responsibility. It is the responsibility of the bidders to comply with those laws as enforced by those various governmental bodies.

The existing paint being removed from these bridges may contain lead or chromium. The Contractor is responsible to assure that workers take proper safety precautions when working in this environment (see bid proposal note entitled "Safety").

Hazardous Waste: If the tests reveal that the maximum concentration of either lead or chromium exceeds 5.0 milligrams per liter, the waste shall be treated as a hazardous waste and the steel containers shall be labeled as a hazardous waste. The Director will then obtain a generator number assigned to **the State.**

All containers of waste material which have been classified as hazardous shall be stored in a secured location until proper disposal. The storage site shall be surrounded with 5 foot (1.5 m) high chain link fence fabric supported by traffic sign drive posts at 10 foot (3 m) center to center. Drive posts shall be embedded into the ground at least 2 feet (0.6 m) deep. The fencing shall be secured with padlocks at the end of each day. Signs shall be posted in obvious locations on the enclosure warning of the hazardous material.

The Contractor shall then arrange for hauling, treating and disposal of all hazardous waste. All hazardous waste shall be disposed of after the Director has obtained a generator number. In every case, any and all hazardous waste shall be disposed of within 60 days after it is generated. Failure to comply with the 60 day disposal requirement shall be considered by the Department as a breach of contract by the Contractor and all abrasive blasting and painting of structural steel on the project shall immediately cease until the hazardous waste is properly disposed. Upon such breach, the Department shall cease processing all pay estimates and notification of the breach shall be sent to the Contractor's surety. Further, any fines or liens assessed by any governmental agency which has jurisdiction over the disposal of this material shall be the responsibility of the Contractor. The hauling and disposal shall be by a firm licensed by U.S. EPA and who shall also be responsible for providing the Uniform Hazardous Waste Manifest (EPA Form 8700-22A).

The Contractor shall decontaminate or dispose of all collection/ containment equipment in accordance with EPA guidelines.

Non-Hazardous Solid Waste: If the waste is determined to be non- hazardous as verified by test results which have been reviewed by the Director, it shall be hauled and disposed of at a facility which is licensed to accept non-hazardous solid waste. Prior to disposal of any material, the Contractor shall submit the test results and documentation that the disposal facility is licensed by the EPA to accept nonhazardous solid waste, to the Engineer. The Contractor shall obtain and provide the Engineer with a receipt documenting disposal of waste material at the approved landfill.

D. Abrasive Blasting (QCP #4). Prior to any abrasive blasting, all dirt, sand, bird nestings, bird droppings and other debris shall be completely removed from the scuppers, bulb angles, pier and abutment seats.

All steel to be painted shall be blast cleaned according to SSPC-SP10 and as shown SSPC-Vis 1-89 (pictorial surface preparation standards for painting steel surfaces). Steel shall be maintained in a blast cleaned condition until it has received a prime coat of paint.

The back side of end cross frame assemblies which are 3 inches (75 mm) or closer to backwalls may be commercial blast cleaned according to **SSPC-SP6.**

Galvanized steel (including corrugated steel bridge flooring), adjacent concrete which has been coated or sealed, and other surfaces not intended to be painted, shall be covered and protected to prevent damage from blasting and painting operations. Any adjacent coatings damaged during the blasting operation shall be repaired at the Contractor's expense.

The abrasive shall be a recyclable steel, ferric oxide, or aluminum oxide grit. After each use and prior to reuse, the grit shall be cleaned of paint chips, rust, mill scale and other foreign material by equipment specifically designed for such cleaning. The Contractor is responsible for assuring recycling and cleaning equipment is capable of operating with the chosen blasting media.

Abrasives shall also be checked for oil contamination before use. A small sample of abrasives shall be added to ordinary tap water. Any detection of a oil film on the surface of the water shall be cause for rejection. This test shall be conducted on each load of abrasives delivered to the job site.

The resultant surface profile shall be a minimum of 1.5 mils (40 μm) and a maximum of 3.5 mils (90 μm). Abrasives of a size suitable to develop the required surface profile shall be used. Any abrasive blasting which is done when the steel temperature is less than 5° F (3° C) above the dew point shall be reblasted when the steel temperature is at least 5° F (3° C) above the dew point. Dew point shall be defined as the temperature at which moisture condenses on the steel surfaces.

All abrasives and residue shall be removed from all surfaces to be painted. All steel blast cleaned in any one day shall be kept dust free and prime coated the same day. Failure to prime coat the same day will require reblasting before prime coating. No dust or abrasives from adjacent work shall be left on the finish coat. The Quality Control Specialist shall perform the following test (and the Inspectorwill verify) to insure that the air is not contaminated: blow air from the nozzle for 30 seconds onto a white cloth or blotter held in a rigid frame. If any oil or other contaminants are present on the cloth or blotter, abrasive blasting shall be suspended until the problem is corrected and the operation is verified by another test. This test shall be done at the start of each shift and at 4 hour intervals. The abrasive shall be tested for oil contamination at the same time.

Abrasive blasting and painting may take place simultaneously on any one bridge as long as abrasive blasting debris and/or dust by the blowing operation does not come in contact with freshly painted surfaces.

The Material Safety Data Sheet (MSDS) shall be provided at the preconstruction meeting for all abrasives to be used on this project. No work shall start until the MSDS has been submitted.

The Contractor shall provide the Engineer and Inspectors a wash facility with running water to permit washing of face and hands during the surface preparation operation. It shall at all times contain an adequate supply of potable water, soap and towels. The Contractor shall be responsible to properly contain, test and dispose of the waste water. The wash facility shall be located at each bridge site in an area that will not be contaminated by the blasting debris.

E. Prime, Intermediate and Finish Coat Application (QCP #5, #8, & #9). Each coat of paint shall be in a proper state of cure or dryness before the application of succeeding coats. Paint shall be considered ready for overcoating when an additional coat can be applied without the development of any detrimental film irregularities, such as lifting, wrinkling or loss of adhesion of the undercoat. The time interval between coating applications shall be in compliance with manufacturer's written instructions and no more than 30 days between the prime and intermediate coats and 13 days between the intermediate and finish coats. These maximum recoat times include weather related days. No additional time for weather delays will be allowed. Any coat which has cured more than the above allotted time without overcoating shall be removed and the steel reblasted to SP 10.

The completion date (month and year) of the finish coat and the letters OZEU shall be stenciled on the steel in 4 inch (100 mm) letters with a black urethane paint. This date shall be applied at four locations near the end of each outside beam on the outside web visible from the road or as directed by the Engineer.

F. Removing Fins, Tears, Slivers (QCP #6). All fins, tears, slivers or any other burred or sharp edges that become evident after priming, shall be removed by grinding. All ground surfaces shall be retextured to produce a profile of 1.5 to 3.5 mils (40 to 90 gym) and re-primed prior to application of the intermediate coat. The Contractor may also begin removing fins, tears and slivers after blasting and prior to priming.

Temperature and weather restrictions do not apply to this item. Reapplying primer shall comply with weather restrictions.

G. Caulking (QCP #7). Caulking will be performed in areas of the bridge where gaps and crevices are greater then 1/8 inch and also other areas as determined by the contractor where caulking is required to prevent bleed through.

885.07 Testing Equipment. The Contractor shall provide the Engineer the following testing equipment in good working order, for the duration of the project. When the Contractor's people are working at different locations simultaneously, additional test equipment shall be provided for each crew for the type of work being performed. When no test equipment is available, no work shall be performed.

1. A camera with the following features and 5 (unless otherwise specified on plans) rolls of color film: A) Uses self developing color print film, B) Lens with auto focus system, C) Focuses from 2 feet (0.6 m) to infinity, D) Built-in fill flash.

2. One Spring micrometer and 3 rolls of extra-coarse replica tape.

3. One Positector 2000 or 6000, Quanix 2200, or Elcometer A345FBI1; and the calibration plates, 1.5-8 mils and 10-25 mils (38-200 µm and 250-625 µm) as per the NBS calibration standards in accordance with ASTM D 1186.

4. One Sling Psychrometer including Psychometric tables - Used to relative humidity and dew point temperature.

5. Two steel surface thermometers accurate within 2° F (1°C) or One portable infrared thermometer available from:

Model: Raynger ST Series (-18° C to 400° C)
Manufacturer: Raytek Inc.
Santa Cruz, Ca.
(800)227-8074

or approved equal to the portable infrared thermometer

6. Flashlight 2-D cell

7. SSPC Visual Standard for Abrasive Blast Cleaned Steel SSPC-Vis 1-89

8. One Recorder Thermometer capable of recording the date, time, and temperature over a period of at least 12 hours.

885.08 Handling. All paint and thinner shall be delivered to the project site in original, unopened containers with labels intact. Minor damage to containers is acceptable provided the container has not been punctured. Thinner containers shall be a maximum of 5 gallons (19 L).

Paint shall be stored at the temperature recommended by the manufacturer to prevent paint deterioration.

Each container of paint and thinner shall be clearly marked or labeled to show paint identification, component, color, lot number, stock number, date of manufacture, and information and warnings as may be required by Federal and State laws.

All containers of paint and thinner shall remain unopened until required for use. The label information shall be legible and shall be checked at the time of use. Solvent used for cleaning equipment is exempt from the above requirements.

Paint which has livered, gelled or otherwise deteriorated during storage shall not be used: However, thixotropic materials which can be stirred to attain normal consistency may be used. The oldest paint of each kind shall be used first. No paint shall be used which has surpassed its shelf life.

Paint may be considered as eligible for payment for material on hand as specified in 109.07. However, only paint which the Contractor can prove to the Engineer will be used during the construction season shall be eligible for payment. The Contractor shall provide the Engineer calculations indicating the total square feet (m2) of steel to be painted during the construction season. He shall also provide calculations showing the total number of gallons (liters) required. The Contractor shall be responsible to store the paint on the project in such manner to prevent theft and adverse temperatures. He shall provide thermometers capable of monitoring the maximum high and low temperatures within the storage facility. The Contractor is responsible for properly disposing of all unused paint and paint containers.

The Contractor shall furnish shipping invoices for all materials used on the project to the Engineer, prior to use.

885.09 Mixing and thinning. All ingredients in any container of paint shall be thoroughly mixed immediately before use and shall be agitated often enough during application to maintain a uniform composition; however, the primer shall be continuously mixed by an automated agitation system (hand held mixers not allowed). Paint shall be carefully examined after mixing for uniformity and to verify that no unmixed pigment remains on the bottom of the container. The paint shall be mixed with a high shear mixer (such as a Jiffy Mixer). Paddle mixers or paint shakers are not allowed. Paint shall not be mixed or kept in suspension by means of an air stream bubbling under the paint surface. All paint shall be strained after mixing. Strainers shall be of a type to remove only skins and undesirable matter, but not pigment.

No thinner shall be added to the paint without the Engineer's approval, and only if necessary for proper application as recommended by the manufacturer. When the use of thinner is permissible, thinner shall be added slowly to the paint during the mixing process. All thinning shall be done under supervision of the Engineer. In no case shall more thinner be added than that recommended bythe manufacturer's printed instructions. Only thinners recommended and supplied by the paint manufacturer may be added to the paint. No other additives shall be added to the paint.

Catalysts, curing agents, or hardeners which are in separate packages shall be added to the base paint only after the base paint has been thoroughly mixed. The proper volume of catalyst shall then be slowly poured into the required volume of base with constant agitation. Liquid which has separated from the pigment shall not be poured off prior to mixing. The mixture shall be used within the pot life specified by the manufacturer. Therefore only enough paint shall be catalyzed for prompt use. Most mixed, catalyzed paints cannot be stored, and unused portions of these shall be discarded at the end of each working day.

885.10 Coating Application. Coating application will be as follows:

A. General. All structural steel, scuppers, expansion joints (except top surface), steel railing, exposed steel piling, drain troughs and other areas as indicated in the plans shall be painted. Galvanized surfaces shall not be painted unless otherwise noted on plans.

The following methods of application are permitted for use by this specification, as long as they are compatible with the paint being used: brush, spray, or any combination of these methods unless specified differently in the plans. Daubers, small diameter rollers or sheepskins may be used for places of difficult access when no other method is practical and in all cases shall be used where cross-frame angles are located within 2 inches (50 mm) of the bottom flange and where end cross frames are within 6 inches (150 mm) of the backwall and bottom of bottom flanges around bearings less than 6 inches (150 mm) in height.

If the surface is degraded or contaminated after surface preparation and before painting, the surface shall be restored before painting application. In order to prevent degradation or contamination of cleaned surface, the prime coat of paint shall be applied the same day of blast cleaning as required in surface preparation above.

Cleaning and painting shall be so programmed that dust or other contaminants do not fall on wet, newly-painted surfaces. Surfaces not intended to be painted shall be suitably protected from the effects of cleaning and painting operations. Overspray and pigeon droppings shall be removed with a stiff bristle brush, wire screen, or a water wash with sufficient pressure to remove overspray without damaging the paint. The overspray must be removed before applying the next coat. All abrasives and residue shall be removed from painted surfaces, before recoating, with a vacuum system equipped with a brush type cleaning tool.

No visible abrasives from adjacent work shall be left on the finish coat. Abrasives on the finish coat shall be removed.

If brush application of the coating is used, it shall produce a smooth coat. Care shall be taken to work the paint into all crevices, corners, and around all bolt and rivet heads.

B. Spray Application (General). All spray application of paint shall be in accordance with the following:

Primer ingredients shall be kept uniformly mixed in the spray pot or container during application by continuous, automated mechanical agitation (hand held mixers not allowed).

Spray equipment shall be kept clean so that dirt, dried paint and other foreign materials are not deposited in the paint film. Any solvent left in the equipment shall be completely removed before using.

Paint shall be applied in a uniform layer with overlapping at the edges of the spray pattern. The border of the spray pattern shall be painted first; with the painting of the interior of the spray pattern to follow, before moving to the next spray pattern area. A spray pattern area is such that the gun shall be held perpendicular to the surface and at a distance which will ensure that a wet layer of paint is deposited on the surface. The trigger of the gun should be released at the end of each stroke. All bolts and rivet heads shall be sprayed from at least 2 directions or brushed to assure coverage. Flange edges should be striped

If mud cracking occurs, the affected area shall be cleaned to bare metal in accordance with surface preparation above and repainted.

All gaps and crevices 1/8 inch (3 mm) or less shall be filled with primer.

All spray equipment used shall be suitable for use with the specified paint. Paint manufacturer's equipment recommendations shall be followed to avoid paint application problems.

If air spray is used, traps or separators shall be provided to remove oil and condensed water from the air. The traps or separators must be of adequate size and must be drained periodically during operations. The following test shall be made by the Contractor and verified by the Engineer to insure that the traps or separators are working properly.

Air shall be blown from the spray gun for 30 seconds onto a white cloth or blotter held in a rigid frame. If any oil, water or other contaminants are present on the cloth or blotter, painting shall be suspended until the problem is corrected and the operation is verified by repeating this test.

This test shall be made at the start of each shift and at 4 hour intervals. This is not required for an airless sprayer.

Spray application of all coats shall not be used unless the operation is totally enclosed to prevent overspray damage to the ground, public and private property, any and all vegetation, streams, lakes, etc. This containment shall be accomplished with tarps, plywood or other shields. If brush is used, more than one coat may be necessary to produce the required thickness.

C. Application Approval. The beginning of the application of each of the three different coats shall be subject to inspection and approval to detect any defects which might result from the Contractor's methods. If defects are discovered, the Contractor shall make all necessary adjustments to his method of application to eliminate them before proceeding with coat application.

D. Temperature. Paint shall not be applied when the temperature of the air, steel, or paint is below 50° F (10°C). Paint shall not be applied when the steel surface temperature is expected to drop below 50° F (10° C) before the paint has cured for the minimum times specified below:

	50° F (10° C)	60° F (16° C)	70° F (21° C)
Primer	4 hrs.	3 hrs.	2 hrs.
Intermediate	6 hrs.	5 hrs.	4 hrs.
Finish	8 hrs.	6 hrs.	4 hrs.

The above temperatures and times shall be monitored with the recording thermometer.

A heated enclosure may be used. The heat within the enclosure may be supplied by any means which will maintain the required temperature continuously and uniformly in all parts of the enclosure. The heat will be supplied as required to maintain the required minimum temperature until the coating has cured.

If combustion type heating units are used, they will be vented away from the enclosure, and exhaust fumes will not be **permitted to enter the enclosure.** No open combustion of any kind will be permitted in the enclosure.

E. Moisture. Paint shall not be applied when the steel surface temperature is less than 5° F (3° C) above the dew point. Paint shall not be applied to wet or damp surfaces or on frosted or ice-coated surfaces. Paint shall not be applied when the relative humidity is greater than 85%. Paint shall not be applied during rain, fog or mist unless the above moisture criteria is met.

F. Repair Procedures. Damaged areas, and areas which do not comply with the requirements of this specification, shall have the paint removed and all defects corrected. The steel should then be retextured to a near white condition to produce a profile of between 1.5 to 3.5 mils (40 to 90 um). This profile should be measured immediately prior to the application of the prime coat to insure that the profile is not destroyed during the feathering procedure.

The existing paint should be feathered to expose a minimum of 1/2 inch (13 mm) of each coat.

During the re-application of the paint, care shall be used to insure that each paint coat is applied only within the following areas. The prime coat shall only be applied to the surface of the bare steel and the existing prime coat which has been exposed by feathering. The prime coat shall not be applied to the adjacent intermediate coat. The intermediate coat shall only be applied to the new prime coat and the existing feathered intermediate coat. The intermediate coat shall not be applied to the adjacent finish coat. The finish coat shall only be applied to the new intermediate coat and the existing finish coat which has been feathered or lightly sanded. The finish coat shall not extend beyond the areas which have been feathered or lightly sanded.

At the perimeter of the repair area, the first two coats shall be applied by brush. The finish coat shall be applied by either brush or spray.

It may be necessary to make several applications in order to achieve the proper thickness for each coat.

During the application of the prime coat, the paint shall be continuously mixed.

All surface preparation and painting shall still be done in accordance with the specifications. In lieu of abrasive blasting, alternate methods of surface preparation may be allowed.

All repairs shall be made in a manner to blend the patched area with the adjacent coating. The finished surface of the patched area shall have a smooth, even profile with the adjacent surface.

The Contractor shall submit his method of correcting runs in writing to the Director for approval.

G. Continuity. Each coat of paint shall be applied as a continuous film of uniform thickness free of all defects such as holidays, runs, sags, etc. All thin spots or areas missed shall be repainted and permitted to dry before the next coat of paint is applied.

H. Dry Film Thickness. Prime thickness, cumulative prime and intermediate thickness, and cumulative prime, intermediate and finish thickness shall be determined by use of Type 2 magnetic gage in accordance with the following:

Five separate spot measurements shall be made, spaced evenly over each 100 square feet (9 m^2) of area to be measured. These measurements shall be taken on flanges, webs, cross bracing, stiffeners, etc. Three gage readings shall be made for each spot measurement of either the substrate or the paint. The probe shall be moved a distance of 1 to 3 inches (25 to 75 mm) for each new gage reading. Any unusually high or low gage reading that cannot be repeated consistently shall be discarded. The average (mean) of the 3 gage readings shall be used as the spot measurement. The average of five spot measurements for each such 100 square foot (9 m^2) area shall not be less that the specified thickness. No single spot measurement in any 100 square foot (9 m^2) area shall be less than 80% of the specified minimum thickness nor greater than 150% of the maximum specified thickness. Any one of 3 readings which are averaged to produce each spot measurement, may under run or overrun by a greater amount. The 5 spot measurements shall be made for each 100 square feet (9 m^2) of area as follows:

1. For structures not exceeding 27 m^2 (300 square feet) in area, each 100 square foot (9 m^2) area shall be measured.

2. For structures not exceeding 1,000 square feet (90 m^2) in area, three 100 square foot (9 m^2) areas shall be randomly selected and measured.

3. For structures exceeding 1,000 square feet (90 m^2) in area, the first 1,000 square feet (90 m^2) shall be measured as stated in section 2 and for each additional 1,000 square feet (90 m^2), or increment thereof, one 100 square foot (9 m^2) area shall be randomly selected and measured.

4. If the dry film thickness for any 100 square foot (9 m^2) area (sections 2 & 3) is not in compliance with the requirements of paragraph 1 of this section, then each 100 square foot (9 m^2) area shall be measured.

5. Other size areas or number of spot measurements as specified in the contract plans shall be measured.

Each coat of paint shall have the following thickness measured above the peaks:

	Min. Spec. Thickness mil (μm)	Max. Spec. Thickness mil (μm)	Min Spot mil (μm)	Max Spot mil (μm)
Prime	3.0 mil (75 μm)	5.0 mil (125 μm)	2.4mil (60 μm)	7.5mil (188 μm)
Intermediate	5.0 mil (125 μm)	7.0 mil (175 μm)	4.0 mil (100 μm)	10.5 mil (263 μm)
Sub Total	8.0 mil (200 μm)	12.0 mil (300 μm)	6.4 mil (160 μm)	18.0 mil (450 μm)
Finish	2.0 mil (50 μm)	4.0 mil (100 μm)	1.6 mil (40 μm)	6.0 mil (150 μm)
Total	10.0 mil (250 μm)	16.0 mil (400 μm)	8.0 mil (200 μm)	24.0 mil (600 μm)

Film thicknesses greater than the maximum specified thicknesses that do not exhibit defects (such as runs, sags, bubbles, mudcracking, etc.) and for which the Contractor has received a written statement from the coating manufacturer stating that this excessive thickness is not detrimental, may remain in place at the discretion of the Director.

For any spot or maximum average thickness over 24 mils (600 pm) it will be necessary for the Contractor to prove to the Department that the excess thickness will not be detrimental to the coating system. This shall be accomplished by providing the Director, for approval, certified test data proving that the excessive thickness will adequately bond to the steel when subjected to thermal expansion and contraction. This thermal expansion and contraction test shall take place over five 5 cycles of a temperature ranges from -20° F to 120° F (-29° C to 49° C). After the thermal contraction and expansion cycles have taken place, the tested system shall be subjected to pull off tests and the results compared to the results of pull off tests which have been performed on a paint system with the proper thicknesses. In addition to the certified test results, it will also be necessary for the Contractor to provide the Director a written statement from the paint manufacturer stating that this excessive thickness is not detrimental.

If the Director does not approve the excessive coating thicknesses or the Contractor elects not to provide the required written statement from the paint manufacturer and the certified test results when required, the Contractor, at his own expense, shall remove and replace the coating. The removal and replacement of the coating shall be done as specified in 885.10 F Repair Procedures.

885.11 Caulking QCP #7. The material shall be a two component, 100% solids epoxy and shall be one of the following:

Mark 270 Poly-Carb Solon, OH 216-248-1223	KOP-COAT A-788 Splash Zone Compound Carboline Company Hamilton, OH 513-896-1919
Sikadur Injection Gel Sika Chemical Corp. Lyndhurst, N.J. 201-933-8801	OR Other Commercially Available, 100% Solid, Non-Sag, Non-Shrink Epoxy Based System Capable Of Filling Voids Up To 25 mm (1 inch) Wide

885.12 Safety Requirements and Precautions. The Contractor shall meet the applicable safety requirements of the Ohio Industrial Commission and the Occupational Safety and Health Administration (OSHA), in addition to the scaffolding requirements specified below.

The Material Safety Data Sheets (MSDS) shall be provided at the preconstruction meeting for all paints, thinners and abrasives used on this project. No work shall start until the MSDS has been submitted.

885.13 Inspection Access. In addition to the requirements of 105.11, the Contractor shall furnish, erect, and move scaffolding and other appropriate equipment, to permit the Inspector the opportunity to closely observe all affected surfaces. This opportunity shall be provided to the Inspector during all phases of the work and continue for a period of at least 10 working days after each structure has been completely painted.

When scaffolding, or the hangers attached to the scaffolding are supported by horizontal wire ropes, or when scaffolding is placed directly under the surface to be painted, the following requirements shall be complied with:

A. When scaffolding is suspended 43 inches (1092 mm) or more below the surface to be painted, two guardrails shall be placed on all sides of the scaffolding. One guardrail shall be placed at 42 inches (1067 mm) above the scaffolding and the other guardrail at 20 inches (508 mm) above the scaffolding.

B. When the scaffolding is suspended at least 21 inches (533 mm) but less than 43 inches (1092 mm) below the surface to be painted, one guardrail shall be placed on all sides of the scaffolding at 20 inches (508 mm) above the scaffolding.

C. Two guardrails shall be placed on all sides of scaffolding not previously mentioned. The guardrails shall be placed at 42 inches (1067 mm) and 20 inches (508 mm) above scaffolding, as previously mentioned.

D. All scaffolding must be at least 24 inches (610 mm) wide when guardrail is used and 28 inches (711 mm) wide when the scaffolding is suspended less than 21 inches (533 mm) below the surface to be painted and guardrail is not used. If 2 or more scaffolding are laid parallel to achieve the proper width, they must be rigidly attached to each other to preclude any differential movement.

E. All guardrail shall be constructed as a substantial barrier which is securely fastened in place and is free from protruding objects such as nails, screws and bolts. There shall be an opening in the guardrail, properly located, to allow the Inspector access onto the scaffolding.

F. The rails and uprights shall be either metal or wood. If pipe railing is used, the railing shall have a nominal diameter of no less than 1.5 inches (38 mm). If structural steel railing is used, the rails shall be 2x2x3/8 inch (50x5Ox9 mm) steel angles or other metal shapes of equal or greater strength. If wood railing is used, the railing shall be 2x4 inches (50x100 mm) (nominal) stock. All uprights shall be spaced at no more than 8 feet (2.4 m) on center. If wood uprights are used, the uprights shall be 2x4 inches (50x100 mm) (nominal) stock.

G. When the surface to be inspected is more than 15 feet (4.57 m) above the ground or water, and the scaffolding is supported from the structure being painted, the Contractor shall provide the Inspector with a safety harness (not a safety belt) and lifeline. The lifeline shall not allow a fall greater than 6 feet (1.8 m). The Contractor shall provide a method of attaching the lifeline to the structure independent of the scaffolding, cables, or brackets supporting the scaffolding.

H. When scaffolding is more than 2.5 feet (762 mm) above the ground, the Contractor shall provide a ladder for access onto the scaffolding. The ladder and any equipment used to attach the ladder to the structure shall be capable of supporting 250 pounds (113 kg) with a safety factor of at least four. All rungs, steps, cleats, or treads shall have uniform spacing and shall not exceed 12 inches (305 mm) on center. At least one side rail shall extend at least 36 inches (914 mm) above the landing near the top of the ladder.

I. An additional landing shall be required when the distance from the ladder to the point where the scaffolding may be accessed, exceeds 12 inches (305 mm). The landing shall be a minimum of at least 24 inches (610 mm) wide and 24 inches (610 mm) long. It shall also be of adequate size and shape so that the distance from the landing to the point where the scaffolding is accessed does not exceed 12 inches (305 mm). The landing shall be rigid and firmly attached to the ladder; however, it shall not be supported by the ladder. The scaffolding shall be capable of supporting a minimum of 1000 pounds (454 kg).

J. In addition to the aforementioned requirements, the Contractor shall be responsible to observe and comply with all Federal, State and local laws, ordinances, regulations, orders and decrees.

K. The Contractor shall furnish all necessary traffic control to permit inspection during and after all phases of the project.

885.14 Protection of Persons and Property. The Contractor shall collect, remove and dispose of all buckets, rags or other discarded materials and shall leave the job site in a clean condition.

The Contractor shall protect all portions of the structure, which are not to be painted, against damage or disfigurement by splashes, spatters, and smirches of paint. Deck bottoms and backwalls are exempt from this requirement.

When or where any direct or indirect damage or injury is done to public or private property, the Contractor shall restore, at his own expense, such property, to a condition similar or equal to that existing before such damage or injury was done.

885.15 Pollution Control The Contractor shall take all necessary precautions to comply with pollution control laws, rules or regulations of Federal, State or local agencies and as required in this specification.

885.16 Work Limitations. Abrasive blasting and painting shall be done between April 1 and October 31. Even though the Contractor is permitted to work prior to May 1, April is considered a winter month and no extension due to adverse weather conditions will be granted for this period. Additional work limitations on specific bridges/projects may be required by plan note.

885.17 Warranty Evaluation Review. During the month before the end of the specified warranty period, the Engineer will inspect the bridge thoroughly for the paint system defects listed. This inspection will be performed jointly by ODOT personnel and Contractor with equipment provided by the Contractor. The inspection equipment shall be OSHA approved, vehicle-mounted, and provide access to all areas of the structure. The Engineer will determine if there are defective areas present as defined in section 885.03 and define those areas.

Traffic control and required signing are the Contractor's responsibilities to supply for the warranty evaluation inspection. The Contractor's traffic control plan shall be in accordance with the Ohio Manual of Uniform Traffic Control Devices and/or as detailed in the plans, and shall be submitted to the District Construction Engineer for approval before inspection is performed.

885.18 Warranty Corrective Work. All defective areas identified by the Engineer at anytime during the warranty period shall be repaired by the Contractor in accordance with this specification's repair procedures. A progress schedule shall be submitted in writing to the Engineer prior to any work. All paint repair work will be done the same season as the inspection, unless the seasonal limitations ofthis specification prevents the completion that season. If that is the case, corrective work will be completed the following season. Any additional defective areas that appear between the time of inspection and the actual corrective work being performed will also be repaired. The Engineer shall be given at least two weeks notification before the Contractor begins the corrective work and shall be allowed full inspection of all operations as per Section 885.13.

Traffic control and required signing are the Contractor's responsibilities to supply for the period of corrective work. The Contractor's traffic control plan shall be submitted to the District Construction Engineer for approval before inspection is performed.

885.19 Method of Measurement. Field painting of structural steel will be paid based on a lump sum basis. All field painting will include 3 coats of paint; prime coat, intermediate coat, and finish coat.

Caulking: Includes all labor, materials and equipment to perform the necessary caulking. This work shall be included with the prime coat for payment.

Surface Preparation: This lump sum item includes all labor, materials and equipment necessary to: perform the necessary solvent cleaning, grind flange edges, grinding fins, tears, slivers, contain, collect, store, evaluate, ship, treat and dispose of all waste materials generated by this project and to prepare the surface as required by these specifications, prior to applying the prime coat.

885.20 Basis of Payment. Payment for field painting, items Surface preparation of existing steel with warranty; Field painting of existing steel, prime coat, with warranty; Field painting of existing steel, intermediate coat, with warranty; Field painting of existing steel, finish coat, with warranty, will be made at the contract prices bid.

These items shall include all costs associated with providing the bridge painting of existing steel with warranty, which shall include maintaining traffic during warranty evaluation, additional insurance, and labor, equipment, and materials necessary to complete the warranty repair work required in conformance with the pertinent repair provisions of this specification, and to the satisfaction of the Engineer.

Item	Unit	Description
885	Lump sum	Surface preparation of existing steel with warranty
885	Lump sum	Field painting of existing steel, prime coat, with warranty
885	Lump sum	Field painting of existing steel, intermediate coat, with warranty
885	Lump sum	Field painting of existing steel, finish coat, with warranty

Appendix D: Second Interim Report about the Performance of MDOT Warranty Clause

OFFICE MEMORANDUM

DATE: January 11, 1996

TO: Jon W. Reincke
Engineer of Research

FROM: Dave Long
Supervisor
Chemical Technology Unit

SUBJECT: **Second Interim Report - Performance Warranty for Bridge Painting Research Project 90 TI-1515**

This report updates the status of structures completed or inspected since the February 4, 1994 report (Table 1). At this report date, all structures in the study have been coated. The last two warranty projects were coated in 1995 and will have their two-year inspections in 1997. After any needed repairs have been made to these structures, the final report will be written in 1998 and the research project closed out.

The most common deficiencies noted during the two-year inspections conducted in 1994 and 1995 were: pinpoint rust on bottom edge of bottom flange, runs, sags, and top coat peeling (see attached field reports for details). None of these deficiencies were major, but all projects require some spot repair by the original contractor or MDOT maintenance forces.

The initial conclusion from the previous report still holds true: a warranty provision does not ensure higher initial quality. Seven warranty and control pairs have had their two-year inspections with no significant differences between the quality of warranty and non-warranty jobs. It appears that repairs will be needed within the first two years of any major coating job. However, the warranty provision does provide the department with an easy mechanism to perform initial repairs at the contractor's expense and not have to rely on maintenance forces.

Cost on all projects in the study ranged from a low of $3.48 to a high of $10.95 per square foot, and covered the time period from 1989 to 1994. Inflation and changing containment requirements probably had more of an impact on cost than the warranty provision. There was no correlation between cost and warranty provisions: warranty costs ranged from being equal to, higher or lower than control projects. A warranty is just one of many factors that determine the final project cost, such as time of year, how busy the contractor is, etc. Since warranty provisions do not seem to change the final costs and provide an additional benefit to the department, they should be used on as many coating projects as possible.

MATERIALS & TECHNOLOGY DIVISION

DC Long

DCL:nc
Attachments
cc FHWA Administrator
G. Bukoski
S. Kulkarni
K. Whelton
R. E. Nordlund

TABLE 1. Updated status of warranty bridges - 11/95

Dist	Type	Control Section	Structure	Cost/Ft²	Status	Comments
1	Warranty Control	B01 of 31012 None	US-41/Portage Lake	NA	Completed 1995*	Initial due in 1996
2	Warranty	B01 of 49023	US-2/Cut River	10.95	2-year inspection*	A few areas of topcoat peeling; very few runs & sags; pack rust under scaffolding support points; damaged coating from moving scaffolding; deficient coating on missed rivet heads.
2	Control	B03 of 51021	US-55/Pine River	6.40	2-yr. inspection	Small areas of pinhole rust; limited paint over debris; limited staining.
3	Warranty Control	B01 of 15012 None	US-31/Island Lake Outlet	13.61	Completed 1995*	Initial due in 1996
4	Warranty	R01 of 20014	I-75 SB/D&M RR	6.95	2-yr. inspection	Limited peeling, staining, paint over debris, & thick paint over mill scale.
4	Warranty	R02 of 20014	I-75 NB/D&M RR	6.95	2-yr. inspection	No peeling; limited staining, paint over debris, & thick paint over mill scale.
4	Control	R01 of 49025	I-75/Soo Line RR	8.24	2-year inspection*	Replaces R01 of 16091. Random runs & sags throughout; some pinpoint rust on edges of flanges and bottom of bottom flange; pack rust on top end of diaphragms on random joints.
4	Warranty	S01 of 20015	I-75/N. Down River Road	6.95	2-yr. inspection	Limited peeling, paint over debris & rust; limited staining at joints.
4	Control	S06 of 76023	I-69/Vernone Road	8.02	2-yr. inspection	Peeling in EB lane; very limited rusting.
5	Warranty	S19 of 41027	I-196/Eastern Ave.	NA	Completed 1993	2-yr. inspection in 1996.
5	Control	S11 of 41029	I-196/M-45	6.80	2-yr. inspection	Very limited rusting; peeling areas repaired.

Dist	Type	Control Section	Structure	Cost/Ft^2	Status	Comments
5	Warranty	S20 of 41027	I-196/Diamond Ave.	NA	Completed 1993	2-yr. inspection in 1996.
5	Control	S12 of 41029	I-196EB/M-45	6.80	2-yr. inspection	Very limited rusting; peeling limited to two square feet.
6	Warranty	S04 of 73171	I-75/Busch Rd.	6.50	2-yr. inspection	Limited peeling; rust at almost every rivet & crevice.
6	Warranty	S05 of 73171	I-75/E. Townline Rd.	6.50	2-yr. inspection	No peeling visible from the ground; rust at almost every rivet & crevice.
6	Control	S01 of 73111	I-75/Baker Rd.	9.28	2-year inspection*	Pinpoint rust on bolts, slivers, & burs, bottom of bottom flange & over areas of heavy corrosion; deficient top coat on south fascia.
6	Warranty	S06 of 73171	I-75/Curtis Rd.	6.50	2-yr. inspection	Limited peeling; paint thickness insufficient in some areas; limited paint over debris.
6	Control	S03 of 73111	I-75/Hess Rd.	9.28	2-year inspection*	Top-coat peeling on south fascia; pinpoint rust on a few slivers & burs on bottom flange; paint over debris at bearings over piers.
7	Warranty	S04 of 13082	I-94/F Drive NW/I-94 BL	5.15	Completed 1994*	Two-year inspection in 1996.
7	Warranty	X01 of 13082	I-94/Conrail W/I-94 BL	5.15	Completed 1994*	Two-year inspection in 1996.
7	Control	S01 of 13083	I-94/Old US-27	6.81	2-year inspection*	Pinpoint rust at bottom of bottom flange & some rivet heads; pack rust at sole plates & built girders; random runs & sags.
8	Warranty	S08 of 23152	EB I-96/Canal Rd.	5.53	2-yr. inspection	No peeling; extremely limited rust & paint over debris.

Dist	Type	Control Section	Structure	Cost/Ft²	Status	Comments
8	Control	R01 of 41061	M-11/M-21BR	3.48	2-yr. inspection	Very limited rusting & staining in crevices.
9	Warranty	S24 of 50111	I-94/Harper Road	7.42	2-yr. inspection	No peeling; extremely limited areas of painting over debris; extremely limited staining.
9	Control	S22 of 50111	I-94/14 Mile Road	7.42	2-year inspection*	Small amount of pinpoint rust on bottom of bottom flange, along weldment at cover plate, & on slivers & burs.

*Status updated November 1995.

Appendix E: INDOT Pavement Warranty Clause

ASPHALT PAVEMENT, WARRANTED

1. DESCRIPTION. This work will consist of the construction of warranted asphalt pavement in conformance with the lines and grades shown on the plans as directed by the Department and as follows.

The Contractor will be responsible for the warranted asphalt pavement for a period of five (5)-years after the date all warranted asphalt pavement is complete and open to unrestricted traffic. The pavement shall be designed for a 15 year life with an anticipated 15,000,000 ESAL loading over the design life.
The Contractor will establish the Job Mix Formula (JMF) and select all materials. Aggregates must meet requirements as listed in Asphalt Institute Publication SP-2, Superpave Mix Design for New Construction and overlays which are as follows for this project:

Mixtures within 100 mm of the pavement surface:

% crushed one face	100% min.
% crushed two face	100% min.
fine aggregate angularity	45% min.
clay content (sand equivalent)	45 min
thin elongated particles	10% max.

Mixtures below 100 mm of the pavement surface:

% crushed one face	95% min.
% crushed two faces	90% min.
fine aggregate angularity	40% min.
clay content (sand equivalent)	45 min.
thin elongated particles	10% max.

For coarse aggregates the following additional requirements apply:

Los Angeles abrasion [1]	40% max.
Soundness (AASHTO T103, Procedure A)	12% max.
Deleterious	
clay lumps / friable (AASHTO T112)	0.2% max.
Non Durable [2]	4.0% max.
Coke and iron [3]	
Chert [4]	3.0% max.

For fine aggregates the following additional requirements apply:

Soundness (AASHTO T103, Procedure A)	10% max.
Acid Insoluble Content (ITM 202)	
Sand	40% min.
Blast Furnace Slag	25% min.

[1] Los Angeles abrasion (AASHTO T96) requirements shall not apply to blast furnace slag.

[2] Includes soft particles as determined by ITM 206 and other particles which are structurally weak, such as soft sandstone, shale, limonite concretions, coal, weathered schist, cemented gravel, ocher, shells, wood, or other objectionable material. Determination of non-durable

particles shall be made from the total weight of material retained on the 9.5 mm sieve.

[3] Air cooled blast furnace slag and steel slag coarse aggregate shall be free of objectionable amounts of coke and iron.

[4] The bulk specific gravity of chert shall be based on the saturated surface dry condition. The amount of chert less than 2.45 bulk specific gravity, shall be determined on the total weight of material retained on the 9.5 mm sieve.

Alternately aggregate can be used which meet Indiana Class A aggregate requirements.

The minimum grade of binder to be used on this project is PG 64-28. The mixture within the top 25mm of the finished surface will have a maximum nominal top size aggregate of 12.5mm. When slag is furnished as an alternate to natural aggregate, adjustments shall be made to compensate for the difference in specific gravity of the slag compared to natural aggregate as outlined in section 904.02(a).

The Contractor will develop a Quality Control Plan which meets the requirements as outlined in the "Contractor Quality Control Plan Requirements for Performance Warranty Asphalt Concrete" and which is to be submitted to the Department.

The provisions of the warranty work will apply to all asphalt mixtures placed as mainline pavement including the construction joint between the mainline pavement and adjacent materials (shoulders, tapers, and ramps). Section 400 and Section 900 of the Standard Specifications are exempted except 904.02 (a). Shoulders, ramps, acceleration lanes and deceleration. lanes are not included in the warranty requirements and will be constructed under Sections 400 and 900 except density control as per 401.12 (a) shall be required.

2. WARRANTY. Upon completion of all warranted asphalt pavement and opening of the warranted pavement to unrestricted traffic, the Warranty Bond will be in effect for a total of five (5)-years. The warranty bond must be properly executed by a surety company satisfactory to the Department and be payable to the State of Indiana and submitted with the bid.

The warranty bond is $900,000.00 for the warranted asphalt pavement. The bond is intended to insure completion of required warranty work, including payments for all labor, equipment, materials and closure periods used to remediate any warranted pavement distresses.

Upon the final acceptance of the project, the contractual obligations of the contractor are satisfied as long as the pavement continues to meet or exceed the warranted values as defined herein.

All warranty work will be in accordance with Section 5. At the end of the warranty period, the Contractor will be released from further warranty work or responsibility, provided all previous warranty work has been satisfactorily completed and accepted by the Department.

3. CONFLICT RESOLUTION TEAM (TEAM). The scope of the Team includes all issues concerning the warranted pavement relative to distress rate, remediation plan, material selection, and quality control plan.

The Team will consist of two Contractor representatives, two Department (District & Central Office) representatives, and a fifth person mutually agreed upon by both the Department and the Contractor. Any costs for the fifth person will be equally shared between the Department and the Contractor. The Team members will be identified in writing at the pre-construction meeting and will be knowledgeable in the terms and conditions of this warranty and the methods used in the measurement and calculation of pavement distress. Should any impasse develop, the Team will render a final recommendation to the Chief Engineer by a majority vote. Each member has an equal vote.

4. WARRANTY WORK. During the warranty period remedial work will be performed at no cost to the Department and will be based on the results of pavement distress surveys. Remedial work to be performed and materials to be used will be the joint decision of the Contractor and the Department. Prior to proceeding with any warranty work or monitoring, a Miscellaneous Permit shall be obtained from the Department.

Costs for lane closure will be applied for peak and non-peak closure periods using the rates contained in this contract.

During the warranty period, the Contractor may monitor the warranted asphalt pavement using nondestructive procedures. All proposed remedial action(s) will be coordinated with the Department.

Coring, milling or other destructive procedures may not be performed by the Contractor, without prior consent of the Department. The Contractor will not be responsible for damages to the pavement as a result of coring, milling or other destructive procedures conducted by the Department.

The Contractor will have the first option to perform the remedial work. If, in the opinion of the Department, the problem requires immediate attention for safety of the traveling public and the Contractor cannot perform the remedial work within twenty-four (24) hours, the Department has the option to have the remedial work performed by other forces. The Contractor will be responsible to pay for all the costs incurred. Remedial work performed by other forces will not alter the requirements, responsibilities, or obligations of the warranty.

5. PAVEMENT DISTRESS INDICATORS, THRESHOLDS AND REMEDIAL ACTION.

The Department will use the following pavement distress indicators:

- International Roughness Index(IRI)
- Rutt Depth
- Friction Number
- Longitudinal Cracking

The Department procedures contained in the manual "Measurement and Calculation of Pavement Distress Indicators for Warranted Asphalt Pavements" will be used for distress measurements and calculation of pavement distress indicators.

The Department will conduct an initial pavement condition survey within 45 calendar days after substantial completion of the project and annual pavement condition surveys between April 15 and May 15 at no cost to the Contractor. The Contractor will be advised of the survey schedule and the results will be made available to the District, Central Office, Contractor and FHWA within 14 days after completion of the survey. If the Contractor disputes the survey findings, written notification of the dispute will be provided within 30 days. Any such dispute must be based on appraisals of data supplied or additional information performed by a licensed professional engineer in the State of Indiana.

The final condition survey will occur by September 1, 2002. Remedial work, if required, will be completed by October 15, 2002. Written acceptance by the Department will be given following satisfactory completion of any remedial work.

If any of the threshold levels are met or exceeded the Contractor will recommend remedial action. After the remedial action is approved by the Department, the Contractor will perform the remedial work according to the following minimum standards:

Alligator Cracks

Remove and replace distressed layer(s). The removal area to be 150% of the distressed area to a depth not to exceed the warranted pavement

Flushing

Remove and replace distressed surface layer full lane width. The removal area to be 150% of the distressed area.

Longitudinal Cracks

Rout and seal all cracks with rubber crack filling material, or agreed upon equal

Longitudinal Distortion

Remove and replace distressed layer (s) . Removal area to be 110% of the distressed area to a depth not to exceed the warranted pavement

Potholes, Slippage Areas, Raveling, Segregation and Other Disintegrated Areas

Remove and replace the distressed area (s). The removal area to be 150% of the distressed area to a depth not to exceed the warranted pavement

Rutting

Remove and replace distressed layers full lane width.

Low Friction

Micro-surfacing distressed area full lane width.

Warranty requirements for all remediation work will be limited to the life of the original contract warranty.

If any of the threshold levels are met or exceeded and the Contractor does not agree to the pavement distress survey results or, the Department does not agree with the proposed remedial action, the Team will provide a recommendation within 30 days.

Remedial action will be performed on all segments of the project where the threshold levels are met or exceeded. If areas of warranted pavement which are not within the measured area are suspected of meeting or exceeding a threshold level, the Department will conduct a distress survey to see if a threshold level has been met or exceeded. Remedial action will be taken by October 1 of the same calendar year as the survey that indicated the threshold level is met or exceeded. If, anytime during the warranty period, 30 percent or more of the project segments require, or have received remedial action, then the entire project will receive a remedial action. as determined by the Contractor and the Department. If an impasse develops, the Team will make a final recommendation.

If remedial action work or elective/preventive action work performed by the Contractor necessitates a corrective action to the pavement markings, adjacent lane(s) or roadway shoulders, then such corrective action to the pavement markings, adjacent lane(s) and shoulders will be the responsibility of the Contractor.

The threshold values for <u>each 100 meter evaluation </u>section are as follows:

International Roughness Index	2.1 m/km (133 in/mi.)
Rut Depth	9.0 mm (0.35 in)
Longitudinal Cracking (severity 2 or greater)	0 m

Friction Number	25

The friction number must average 35 with no individual value less than 25.

The Contractor will not be held responsible for distresses which are caused by factors beyond the control of the Contractor. For example, the Contractor will be relieved of the responsibility for IRI remedial action if the roughness is caused by alligator cracking providing the pavement in question is of proper thickness (not thinner than 15 mm from plan thickness) and the recovered binder is of acceptable stiffness and one of the following is true: the base is at least 50 mm thinner than plan thickness, or the subgrade density is less than 90% of optimum, or the actual number of Class 5 or higher trucks are 50% above the projected five year number of Class 5 or higher trucks. The five year projected number of Class 5 or higher trucks for this project is 19,800,000.

The rutting threshold level is waived when the accumulated number of Class 5 or higher trucks is 50% above the projected fifth year accumulated number of Class 5 or higher trucks. If the rutting is assumed to be caused by the base or subgrade, coring (or cross sectional sampling) will be conducted to determine the cause of the rutting. The Contractor will only be responsible for mixture and placement problems.

6. ELECTIVE/PREVENTIVE ACTION. Elective/preventive action will be the Contractor's option with the concurrence of the Department. For elective/preventive actions, lane closure periods are not charged.

7. DEPARTMENT MAINTENANCE. The Department will perform routine maintenance during the warranty period such as plowing, applying de-icing chemicals, repairs to safety appurtenances, pavement markings, mowing and sign maintenance. No routine pavement surface maintenance activities will be performed by the Department during the warranty period.

8. METHOD OF MEASUREMENT. Warranted asphalt pavement will be measured for payment by the megagram of mixture based on the quantity of mixture placed. Asphalt mixture will be paid for at the contract unit price for Asphalt Pavement Mixture, Warranted, which will include full compensation for furnishing, preparing, hauling, mixing and placing all materials and compacting the mixtures. The Warranty Bond, warranty work, Job Mix Formula, Quality Control Plan and all testing, record keeping, sampling and traffic control are included in the contract unit prices.

9. BASIC OF PAYMENT. The accepted quantities of asphalt pavement mixtures will be paid for at the contract unit price per megagram for asphalt pavement mixtures warranted which payment will be full compensation for furnishing, preparing, hauling, mixing and placing all materials and compacting the mixtures. The Warranty Bond, warranty work, Job Mix Formula, Quality Control Plan and all testing, record keeping, sampling and traffic control are included in the contract unit price.

Payment will be made under:

Pay Item	Pay Unit
Asphalt Pavement Mixtures, Warranted	Megagram (ton)

Appendix F: Image Acquisition – 1st Extension Study

F.1 Right angle

F.2 60-degree

F.3 45-degree

F.4 Long distance (10 ft)

F.5 Shading

F.6 Image after cleaning at 90-degree angle

F.7 Cropping image (Size: 256x256)

Appendix G: Comparison of Processed Images – 1st Extension Study

G.1 Right angle/ Non-clean

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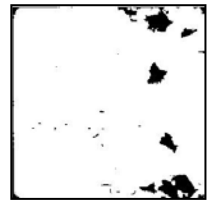
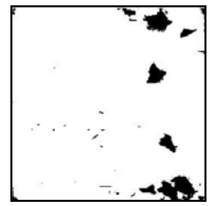
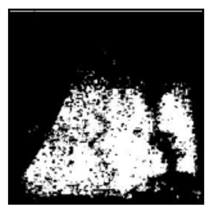
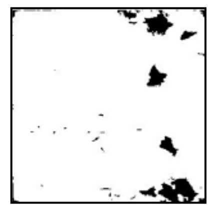
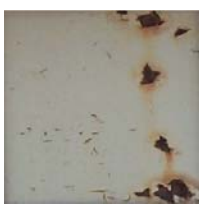
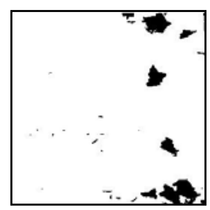
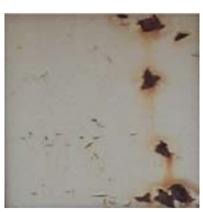
1			
2			
3			
4			
5			

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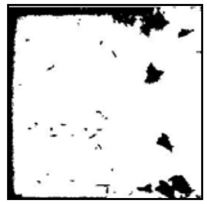
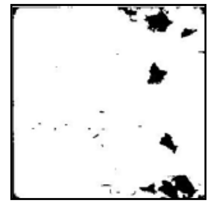
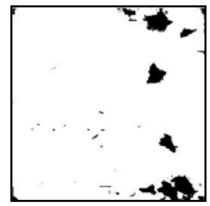
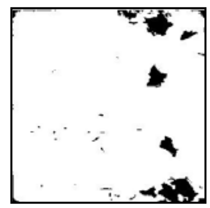
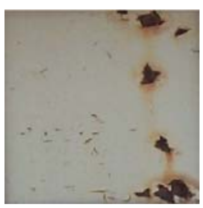
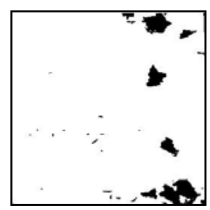
1			
2			
3			
4			
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G.2 60-degree/ Non-clean

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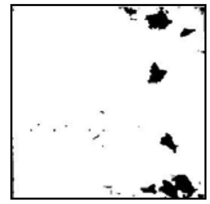
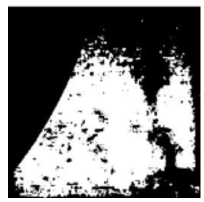
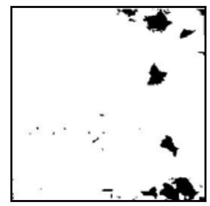
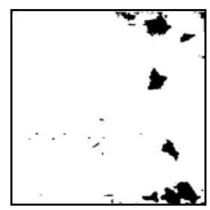
1			
2			
3			
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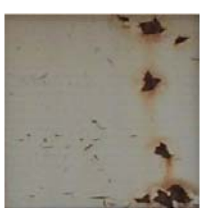
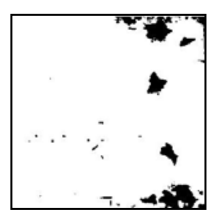
5			

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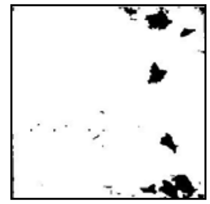
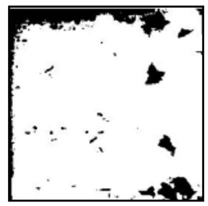
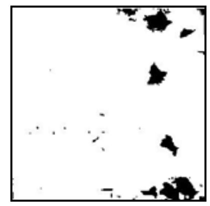
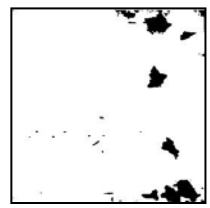
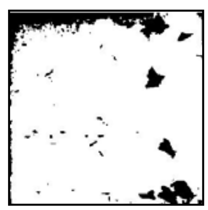
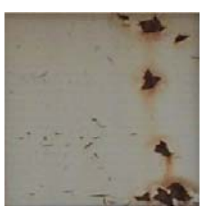
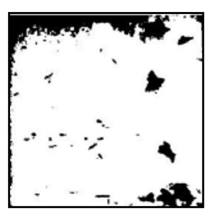
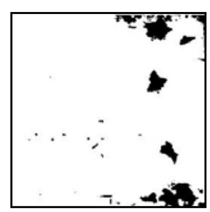
1			
2			
3			
4			
5			

G.3 45-degree/ Non-clean

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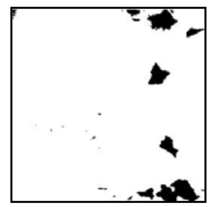
2			
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Image	Color	ISKA	KMNS
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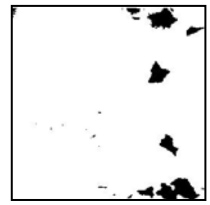
2			
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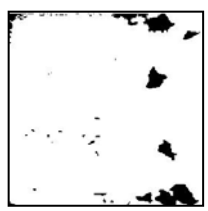
4			
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G.4 Long distance/ Non-clean

Image	Color	NFRA	SKMN
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2			
3			
4			
5			

Image	Color	ISKA	KMNS
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3			
4			
5			

G.5 Shading/ Non-clean

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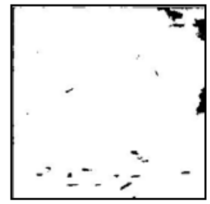
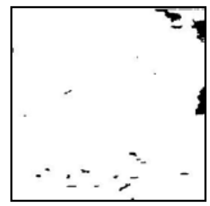
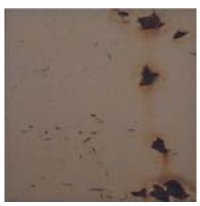
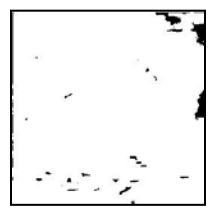
1			
2			
3			
4			
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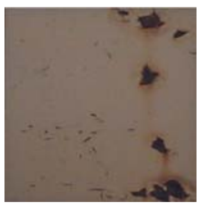
3			
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G.6 Right angle/ Clean

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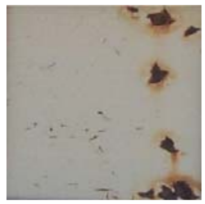
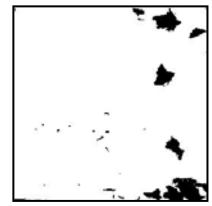
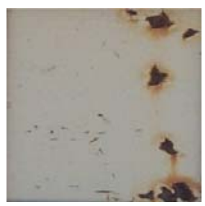
1			
2			
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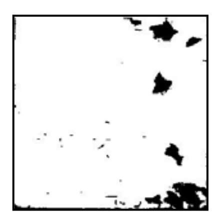
5			

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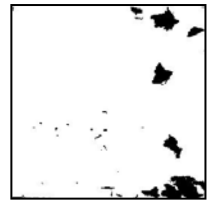
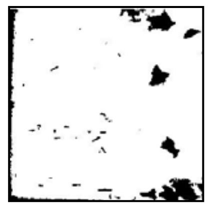
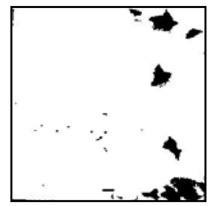
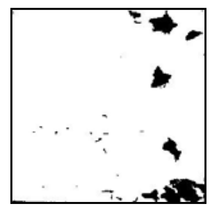
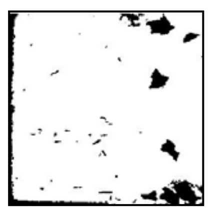
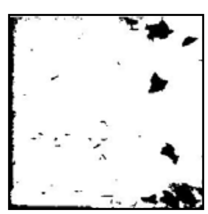
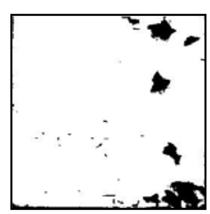
1			
2			
3			
4			
5			

G.7 60-degree/ Clean

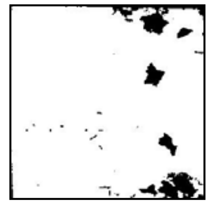
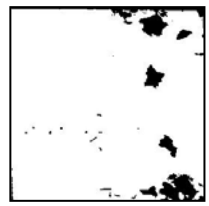
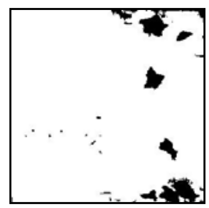
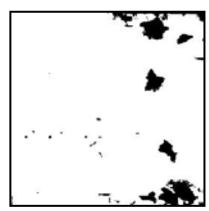
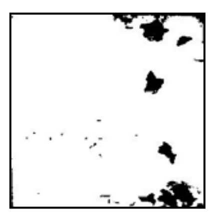
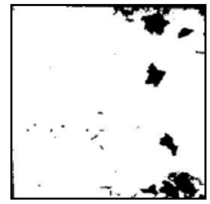
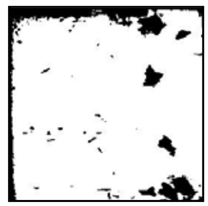
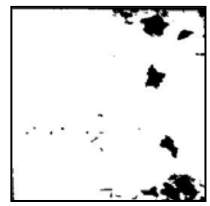
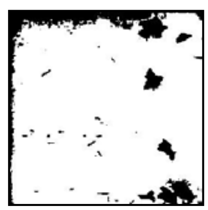
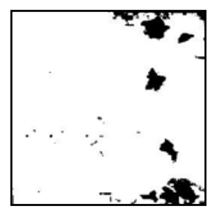
Image	Color	NFRA	SKMN
1			
2			
3			
4			
5			

Image	Color	ISKA	KMNS
1			
2			
3			
4			
5			

G.8 45-degree/ Clean

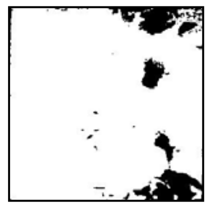
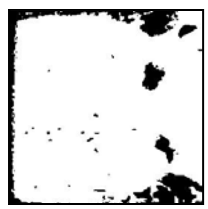
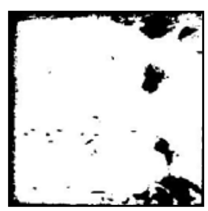
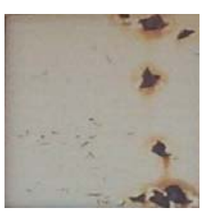
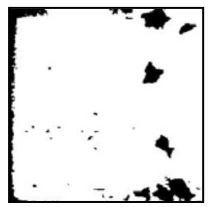
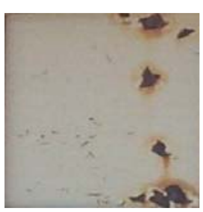
Image	Color	NFRA	SKMN
1			
2			
3			
4			
5			

Image	Color	ISKA	KMNS
1			
2			
3			
4			
5			

G.9 Long distance/ Clean

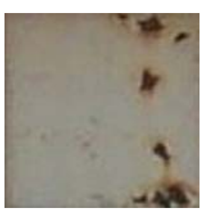
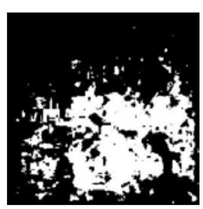
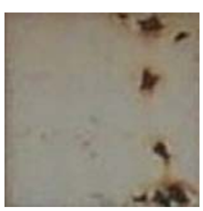
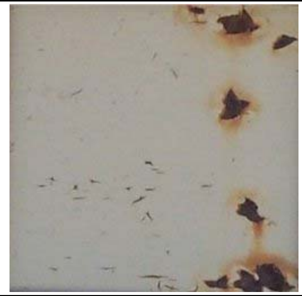
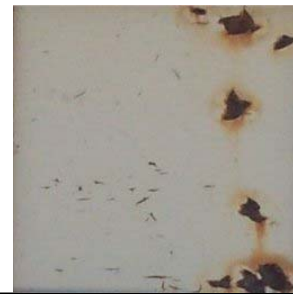
Image	Color	NFRA	SKMN
1			
2			
3			
4			
5			

Image	Color	ISKA	KMNS
1			
2			
3			
4			
5			

Appendix H: Comparison of Non-clean and Clean Images – 1st Extension Study

Image	Non-Clean	Clean
1		
2		
3		
4		
5		

Appendix I: Processed Results from Acquired Images for Objective (1) and (2) – 2nd Extension Study

I.1 Detail results of non-clean images

(1) 90-degree angle/3-foot distance

Conditions	Image	RP (%)	CPU (sec)
90-degree angle/ 3-foot distance	1	1.0223	19
	2	0.8591	17
	3	0.9216	19
	4	0.9903	22
	5	0.8957	20
	6	0.9995	23
	7	1.0406	22
	8	1.0696	22
	9	1.0239	25
	10	0.9689	19
	11	0.9003	14
	12	0.8255	13
	13	0.8499	16
	14	0.8682	19
	15	0.8377	18
	16	0.8835	19
	17	0.8469	19
	18	0.8621	14
	19	1.0208	25
	20	0.9338	22
	21	0.9048	17
	22	0.9430	20
	23	0.9430	19
	24	0.8881	19
	25	0.9766	25
	26	0.9720	19
	27	0.9293	19
	28	0.9125	22
	29	1.0025	25
	30	0.9811	19

(2) 60-degree angle/3-foot distance

Conditions	Image	RP (%)	CPU (sec)
60-degree angle/ 3-foot distance	1	1.0208	19
	2	1.0300	19
	3	0.9781	16
	4	0.9888	19
	5	1.0208	19
	6	0.9155	16
	7	1.0361	20
	8	0.9384	15
	9	1.1459	28
	10	1.0544	19
	11	1.0300	19
	12	1.0727	19
	13	0.9293	16
	14	1.0254	16
	15	1.0513	19
	16	0.9186	20
	17	0.9583	17
	18	1.0132	20
	19	1.0223	19
	20	1.0330	19
	21	0.9964	16
	22	1.1200	25
	23	1.0620	22
	24	1.0208	22
	25	0.9613	19
	26	0.9506	19
	27	0.9476	14
	28	1.0757	22
	29	1.0513	19
	30	1.0468	22

(3) 45-degree angle/3-foot distance

Conditions	**Image**	**RP (%)**	**CPU (sec)**
45-degree angle/ 3-foot distance	1	0.9613	21
	2	0.9918	20
	3	1.0727	19
	4	1.0254	19
	5	1.0208	20
	6	1.0010	17
	7	1.0986	22
	8	1.1017	20
	9	1.0178	19
	10	1.0590	19
	11	1.0178	19
	12	1.0361	17
	13	1.0391	20
	14	1.0315	20
	15	1.0880	20
	16	1.0468	20
	17	0.9979	18
	18	1.0574	19
	19	1.0330	21
	20	1.0269	20
	21	1.0666	20
	22	0.9659	17
	23	1.0300	17
	24	1.0178	16
	25	1.0895	20
	26	1.0590	20
	27	1.0193	17
	28	1.0178	19
	29	1.0162	20
	30	1.0056	19

(4) 90-degree angle/10-foot distance

Conditions	Image	RP (%)	CPU (sec)
90-degree angle/ 10-foot distance	1	1.0330	26
	2	1.3519	35
	3	1.6342	46
	4	1.1383	23
	5	1.1566	20
	6	0.9583	23
	7	1.5442	26
	8	1.3138	28
	9	1.1917	23
	10	1.2863	31
	11	1.4343	32
	12	1.4618	32
	13	1.1902	23
	14	1.0147	22
	15	1.3947	28
	16	1.6663	41
	17	0.9979	20
	18	1.0300	25
	19	1.1902	23
	20	1.0300	20
	21	1.2054	26
	22	1.0727	22
	23	1.0132	15
	24	1.1658	23
	25	1.1337	26
	26	1.1688	23
	27	1.0895	20
	28	0.9293	20
	29	1.5579	38
	30	1.3382	29

I.2 Detail results of clean images

(1) 90-degree angle/3-foot distance

Conditions	Image	RP (%)	CPU (sec)
90-degree angle/ 3-foot distance	1	1.6235	14
	2	1.7227	14
	3	1.7426	14
	4	1.6693	14
	5	1.6556	14
	6	1.6968	14
	7	1.6891	14
	8	1.6953	16
	9	1.7242	14
	10	1.8036	17
	11	1.7029	14
	12	1.6983	14
	13	1.6037	14
	14	1.8005	17
	15	1.7166	14
	16	1.6724	14
	17	1.6525	14
	18	1.7487	14
	19	1.7029	14
	20	1.6891	14
	21	1.6129	14
	22	1.7090	12
	23	1.6891	14
	24	1.6510	15
	25	1.6190	14
	26	1.6724	14
	27	1.6327	14
	28	1.7090	14
	29	1.6693	14
	30	1.7548	14

(2) 60-degree angle/3-foot distance

Conditions	Image	RP (%)	CPU (sec)
60-degree angle/ 3-foot distance	1	1.6998	14
	2	1.7334	14
	3	1.7410	14
	4	1.7365	14
	5	1.7624	12
	6	1.7517	14
	7	1.7410	14
	8	1.7593	17
	9	1.7059	9
	10	1.7044	16
	11	1.7105	14
	12	1.7258	15
	13	1.7792	14
	14	1.7197	14
	15	1.7746	9
	16	1.7365	14
	17	1.6953	11
	18	1.6968	14
	19	1.6907	11
	20	1.7014	14
	21	1.7258	14
	22	1.7395	14
	23	1.7731	11
	24	1.7471	14
	25	1.6876	14
	26	1.7273	15
	27	1.7715	14
	28	1.7761	11
	29	1.7776	14
	30	1.7349	11

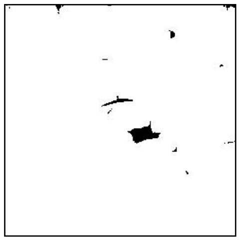
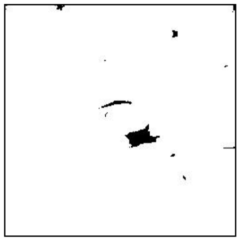
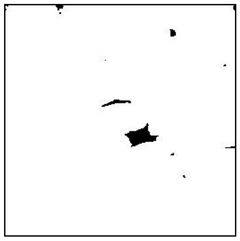
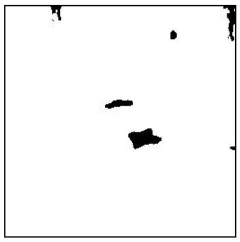
(3) 45-degree angle/3-foot distance

Conditions	Image	RP (%)	CPU (sec)
45-degree angle/ 3-foot distance	1	1.7685	15
	2	1.7624	15
	3	1.7639	15
	4	1.7242	14
	5	1.7380	14
	6	1.7487	11
	7	1.7303	11
	8	1.7242	14
	9	1.6907	11
	10	1.7303	14
	11	1.7792	17
	12	1.6861	14
	13	1.7624	11
	14	1.7151	14
	15	1.7136	11
	16	1.7517	10
	17	1.7288	13
	18	1.7380	13
	19	1.7319	11
	20	1.7014	10
	21	1.7029	11
	22	1.7960	11
	23	1.8158	10
	24	1.8021	11
	25	1.8143	14
	26	1.8356	11
	27	1.8005	11
	28	1.7700	14
	29	1.7929	14
	30	1.7715	15

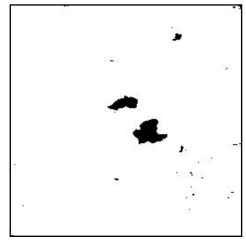
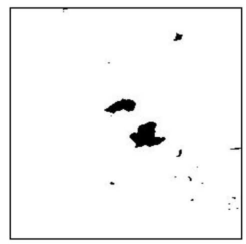
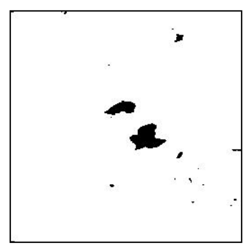
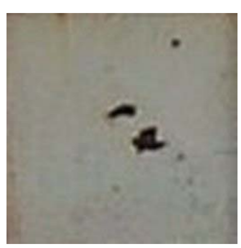
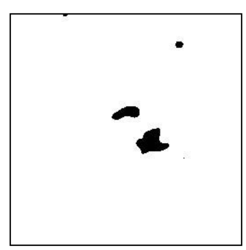
(4) 90-degree angle/10-foot distance

Conditions	Image	RP (%)	CPU (sec)
90-degree angle/ 10-foot distance	1	1.4206	13
	2	1.4847	11
	3	1.4786	16
	4	1.5152	13
	5	1.4816	11
	6	1.5366	19
	7	1.5549	13
	8	1.5686	13
	9	1.5396	16
	10	1.5793	18
	11	1.5320	16
	12	1.4908	13
	13	1.5549	16
	14	1.5808	13
	15	1.5823	13
	16	1.5610	16
	17	1.4786	16
	18	1.5289	13
	19	1.5533	10
	20	1.4847	13
	21	1.4328	12
	22	1.4648	13
	23	1.4679	13
	24	1.5137	13
	25	1.5503	13
	26	1.5732	13
	27	1.4847	16
	28	1.6037	16
	29	1.5549	13
	30	1.5091	13

Appendix J: Sample Processed Images under Non-clean Conditions for Objective (1) and (2) – 2^{nd} Extension Study

Condition	Color	Binary
90-degree angle/ 3-foot distance		
60-degree angle/ 3-foot distance		
45-degree angle/ 3-foot distance		
90-degree angle/ 10-foot distance		

Appendix K: Sample Processed Images under Clean Conditions for Objective (1) and (2) – 2nd Extension Study

Condition	Color	Binary
90-degree angle/ 3-foot distance		
60-degree angle/ 3-foot distance		
45-degree angle/ 3-foot distance		
90-degree angle/ 10-foot distance		

Appendix L: Processed Results from 0.1% Image Template for Objective (3) – 2nd Extension Study

(1) 10 feet

Image	RP (%)	CPU (sec)
1	0.0916	13
2	0.1099	13
3	0.1190	18
4	0.1114	21
5	0.1022	23
6	0.1083	21
7	0.1083	21
8	0.1068	15
9	0.1083	21
10	0.1038	18
11	0.1068	13
12	0.1144	20
13	0.0900	15
14	0.1022	20
15	0.1007	18
16	0.1022	15
17	0.1053	18
18	0.1083	18
19	0.0992	15
20	0.1022	21
21	0.1053	20
22	0.1236	20
23	0.1053	20
24	0.1053	21
25	0.0992	18
26	0.0992	15
27	0.1007	18
28	0.1053	20
29	0.1007	15
30	0.0961	15

(2) 15 feet

Image	RP (%)	CPU (sec)
1	0.0931	20
2	0.0931	17
3	0.0961	17
4	0.1053	23
5	0.1099	20
6	0.0977	14
7	0.0961	20
8	0.0839	15
9	0.1129	20
10	0.0885	14
11	0.0961	14
12	0.0992	17
13	0.0900	14
14	0.1022	17
15	0.0961	17
16	0.0946	17
17	0.0931	13
18	0.0961	17
19	0.0824	15
20	0.0854	15
21	0.0885	15
22	0.0900	20
23	0.0946	15
24	0.0946	14
25	0.0916	20
26	0.0977	17
27	0.1038	17
28	0.1007	20
29	0.0900	15
30	0.1068	17

(3) 30 feet

Image	RP (%)	CPU (sec)
1	0.1602	17
2	0.1556	18
3	0.1724	19
4	0.1709	15
5	0.1724	15
6	0.1633	20
7	0.1511	18
8	0.1663	15
9	0.1816	19
10	0.1495	21
11	0.1617	21
12	0.1480	15
13	0.1587	18
14	0.1755	20
15	0.1770	21
16	0.1633	15
17	0.1633	21
18	0.1816	21
19	0.1511	15
20	0.1511	18
21	0.1663	15
22	0.1617	18
23	0.1724	18
24	0.1755	18
25	0.1663	15
26	0.1740	18
27	0.1617	18
28	0.1450	15
29	0.1617	18
30	0.1740	18

(4) 45 feet

Image	RP (%)	CPU (sec)
1	45.5551	45
2	1.1017	21
3	0.7370	21
4	36.8561	41
5	0.6119	21
6	53.5065	35
7	1.2115	18
8	51.0910	38
9	1.2161	18
10	0.4333	18
11	0.5508	18
12	20.5948	39
13	0.8682	24
14	58.0475	51
15	51.1139	42
16	25.6561	37
17	25.0381	33
18	35.5835	35
19	28.3295	48
20	0.9186	24
21	1.1734	21
22	33.3237	41
23	42.9138	35
24	34.6039	36
25	1.1551	21
26	28.9856	39
27	11.7233	33
28	32.9315	39
29	50.6561	46
30	45.3522	45

(5) 60 feet

Image	RP (%)	CPU (sec)
1	75.8987	24
2	57.7469	15
3	52.3727	15
4	63.3835	18
5	57.8415	15
6	59.6481	27
7	71.8140	24
8	67.8085	24
9	45.8405	18
10	21.1746	33
11	71.7941	15
12	53.2211	27
13	57.5104	18
14	58.3710	21
15	59.1812	30
16	46.0281	27
17	74.1394	27
18	63.8763	30
19	43.9545	36
20	65.5121	27
21	62.6724	30
22	68.2709	24
23	71.1594	27
24	68.9514	16
25	64.3387	19
26	74.3042	27
27	43.4937	19
28	61.2915	24
29	63.0188	21
30	58.5114	33

Appendix M: Processed Results from 0.3% Image Template for Objective (3) – 2nd Extension Study

(1) 10 feet

Image	RP (%)	CPU (sec)
1	0.2518	21
2	0.2472	24
3	0.2594	21
4	0.2655	20
5	0.2594	21
6	0.2548	15
7	0.2853	21
8	0.2487	21
9	0.2579	21
10	0.2502	18
11	0.2640	18
12	0.3082	21
13	0.2792	21
14	0.2747	27
15	0.2747	18
16	0.2518	18
17	0.2594	21
18	0.2670	21
19	0.2563	21
20	0.2487	25
21	0.2823	24
22	0.2701	21
23	0.2716	27
24	0.2731	24
25	0.2747	18
26	0.2533	15
27	0.2533	18
28	0.2777	18
29	0.2579	18
30	0.2579	18

(2) 15 feet

Image	RP (%)	CPU (sec)
1	0.2457	18
2	0.2640	21
3	0.2518	21
4	0.2472	18
5	0.2289	19
6	0.2518	18
7	0.2518	18
8	0.2365	16
9	0.2533	19
10	0.2457	21
11	0.2319	18
12	0.2487	18
13	0.2243	21
14	0.2380	19
15	0.2487	24
16	0.2609	19
17	0.2380	18
18	0.2533	19
19	0.2472	20
20	0.2563	21
21	0.2441	18
22	0.2502	22
23	0.2686	18
24	0.2579	21
25	0.2426	19
26	0.2609	22
27	0.2548	24
28	0.2899	21
29	0.2838	21
30	0.2457	19

(3) 30 feet

Image	RP (%)	CPU (sec)
1	0.4593	19
2	0.4608	18
3	0.4440	21
4	0.4486	21
5	0.4211	14
6	0.4501	21
7	0.4044	18
8	0.4486	18
9	0.4227	18
10	0.4745	18
11	0.4364	15
12	0.4349	21
13	0.5249	18
14	0.4608	19
15	0.4730	22
16	0.4364	19
17	0.4654	21
18	0.4318	18
19	0.4303	19
20	0.4257	18
21	0.4211	15
22	0.4807	21
23	0.4150	19
24	0.4364	16
25	0.4196	18
26	0.4501	18
27	0.4745	18
28	0.4486	18
29	0.4288	19
30	0.4776	18

(4) 45 feet

Image	RP (%)	CPU (sec)
1	0.9232	16
2	1.0849	18
3	0.8652	19
4	0.9171	16
5	1.3962	19
6	1.1383	21
7	1.1337	18
8	1.0391	18
9	1.0681	18
10	1.4526	18
11	0.9766	18
12	1.1688	19
13	1.1307	19
14	1.0452	18
15	0.9369	18
16	0.9781	16
17	1.1902	19
18	1.0727	21
19	1.0788	19
20	1.3794	22
21	0.9567	19
22	0.9186	18
23	0.9323	19
24	1.1322	19
25	0.9506	19
26	0.9476	17
27	1.0956	16
28	1.0376	16
29	1.0910	19
30	0.9552	19

(5) 60 feet

Image	RP (%)	CPU (sec)
1	2.2766	19
2	5.4092	19
3	3.5248	16
4	1.6266	22
5	2.4612	21
6	2.2568	19
7	3.3478	19
8	2.9541	19
9	2.7740	22
10	3.1906	16
11	4.0573	16
12	4.8798	22
13	2.5040	19
14	5.0552	22
15	9.4162	16
16	4.4831	26
17	3.7781	19
18	2.4750	19
19	2.4323	19
20	2.4368	22
21	4.0909	19
22	4.0741	19
23	2.9953	16
24	6.4743	22
25	4.2953	22
26	2.9007	22
27	7.6477	22
28	5.8823	19
29	4.0161	22
30	3.5355	22

Appendix N: Processed Results from 1.0% Image Template for Objective (3) – 2nd Extension Study

(1) 10 feet

Image	RP (%)	CPU (sec)
1	0.9003	14
2	0.9888	15
3	0.9064	15
4	0.9140	17
5	0.9872	13
6	0.9232	14
7	0.9018	18
8	0.9201	15
9	0.8835	19
10	0.9186	15
11	0.9476	15
12	0.9506	18
13	1.0132	15
14	0.9598	16
15	0.9796	18
16	0.9369	15
17	0.9384	14
18	0.9888	18
19	0.8820	15
20	0.9399	18
21	0.9552	15
22	0.9384	15
23	1.0330	12
24	0.9776	18
25	0.9735	15
26	0.9689	16
27	0.9689	15
28	0.9689	18
29	0.9720	18
30	0.9720	15

(2) 15 feet

Image	RP (%)	CPU (sec)
1	0.8957	19
2	0.8423	18
3	0.8850	18
4	0.8408	18
5	0.8652	18
6	0.8850	21
7	0.8652	18
8	0.8743	22
9	0.8606	18
10	0.8713	18
11	0.8560	18
12	0.8484	18
13	0.8713	18
14	0.8850	22
15	0.8896	21
16	0.8591	18
17	0.9094	18
18	0.9216	21
19	0.8423	18
20	0.8652	18
21	0.8469	15
22	0.8377	16
23	0.8606	18
24	0.8789	18
25	0.9079	19
26	0.8591	18
27	0.8804	18
28	0.8118	18
29	0.8362	18
30	0.8270	21

(3) 30 feet

Image	RP (%)	CPU (sec)
1	0.7706	21
2	0.7996	26
3	0.7751	21
4	0.8224	21
5	0.7797	21
6	0.8453	21
7	0.7996	23
8	0.7462	24
9	0.8118	21
10	0.8240	21
11	0.7690	23
12	0.8514	23
13	0.8514	21
14	0.7629	24
15	0.8255	24
16	0.8530	24
17	0.8163	24
18	0.7874	21
19	0.8469	24
20	0.7614	21
21	0.7767	21
22	0.8316	23
23	0.7919	20
24	0.8041	24
25	0.8469	24
26	0.8301	21
27	0.7782	21
28	0.8011	23
29	0.7889	21
30	0.8133	21

(4) 45 feet

Image	RP (%)	CPU (sec)
1	1.0513	28
2	1.0757	19
3	1.0544	24
4	1.0849	24
5	1.0513	26
6	1.0239	25
7	1.0742	29
8	1.1154	28
9	1.0971	25
10	1.0178	24
11	1.0178	22
12	1.0605	25
13	1.0956	30
14	0.9964	24
15	1.0498	21
16	0.9735	27
17	1.0239	25
18	1.0849	21
19	1.0895	28
20	1.0666	31
21	1.0345	19
22	1.0452	29
23	1.0971	28
24	1.0651	27
25	1.0361	28
26	1.0300	25
27	1.0513	25
28	0.9766	25
29	1.0696	25
30	1.0483	24

(5) 60 feet

Image	RP (%)	CPU (sec)
1	1.7990	25
2	1.8417	25
3	1.6632	25
4	1.6556	25
5	1.6556	22
6	1.7151	25
7	1.6800	29
8	1.7548	25
9	1.8646	26
10	1.6083	26
11	1.6724	26
12	1.7044	23
13	1.5976	26
14	1.4893	26
15	1.7517	25
16	1.8066	22
17	1.7838	27
18	1.6846	26
19	1.7502	28
20	1.7380	25
21	1.7258	25
22	1.6602	26
23	1.7517	22
24	1.6541	30
25	1.7532	26
26	1.7685	26
27	1.5900	26
28	1.8188	25
29	1.7242	26
30	1.7334	27

Appendix O: ASTM Standards

Standard Test Method for Evaluating Degree of Rusting on Painted Steel Surfaces[1]

This standard is issued under the fixed designation D 610; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This method has been approved for use by agencies of the Department of Defense to replace Method 6451 of Federal Test Method Standard No. 141A. Consult the DoD Index of Specifications and Standards for the specific year of issue which has been adopted by the Department of Defense.

1. Scope

1.1 This test method covers the evaluation of the degree of rusting on painted steel surfaces using visual standards. These visual standards[2] were developed in cooperation with the Steel Structures Painting Council (SSPC) to further standardization of methods.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Document

2.1 *Adjunct:*

D 610 Degree of rust (four photos)[2]

3. Significance and Use

3.1 The amount of rusting beneath or through a paint film is a significant factor in determining whether a coating system should be repaired or replaced. This test method provides a standardized means for quantifying the amount of rust present.

4. Interferences

4.1 The colored photographic reference standards that are part of this test method and the associated rust-grade scale cover only rusting not accompanied by blistering and evidenced by visible rust.

4.2 The use of the photographic reference standards[2] requires the following cautions:

4.2.1 Some finishes are stained by rust. This staining must not be confused with the actual rusting involved.

4.2.2 Accumulated dirt or other material may make accurate determination of the degree of rusting difficult.

4.2.3 Certain types of deposited dirt that contain iron or iron compounds may cause surface discoloration that should not be mistaken for corrosion.

4.2.4 Failure may vary over a given area and discretion must therefore be used when selecting a single grade that is to be representative of a large area or structure.

4.2.5 The color of the finish coating should be taken into account in evaluating surfaces as failures will be more apparent on a finish that shows color contrast with rust, such as used in these reference standards, than on a similar color, such as an iron oxide finish.

5. Procedure

5.1 Visually compare the surface with the photographic reference standards to determine the percentage of the area rusted. As a guide use Fig. 1 and the scale and verbal descriptions shown in Table 1.

NOTE 1—The numerical rust grade scale is an exponential function of the area of rust so that slight amounts of first rusting have the greatest affect on lowering the rust grade; the rust grade versus area of rust is a straight line plot on semilogarithmic coordinate from rust grade 10 to rust grade 4. The slope of the curve was changed at 10 % of the area rusted to 100 % rusted to permit inclusion of complete rusting on the 0 to 10 rust scale.

NOTE 2—The pictorial representations illustrated in Fig. 1[3] show examples of area percentages that may be helpful in rust grading.

5.2 The photographic reference standards are not required for use of the rust-grade scale since the scale is based upon the percent of the area rusted and any method of assessing area rusted may be used to determine the rust grade.

6. Precision and Bias

6.1 No precision or bias statement can be made for this test method.

7. Keywords

7.1 corrosion; rusting

[1] This test method is under the jurisdiction of ASTM Committee D-1 on Paint and Related Coatings, Materials, and Applications and is the direct responsibility of Subcommittee D01.46 on Industrial Protective Coatings.

This test method has been jointly approved by ASTM and the Steel Structures Painting Council.

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[2] The colored photographic reference standards are available at a nominal cost from ASTM Headquarters (request Adjunct No. 12-406100-00), and from the Steel Structures Painting Council, 4518 Henry St., Suite 301, Pittsburgh, PA 15213.

[3] Original source is *Steel Structures Painting Manual*, Vol 2, Steel Structures Painting Council, Pittsburgh, PA.

TABLE 1 Scale and Description of Rust Grades

NOTE—SSPC Initial Surface Conditions E, F, G, and H are described in "Systems and Specifications, Surface Preparation Commentary," Vol 2 of the *Steel Structure Painting Manual*, 6th Edition, 1991.

Rust Grades[A]	Description	ASTM-SSPC Colored Photographic Standard
10	no rusting or less than 0.01 % of surface rusted	unnecessary
9	minute rusting, less than 0.03 % of surface rusted	No. 9
8[B]	few isolated rust spots, less than 0.1 % of surface rusted	No. 8
7	less than 0.3 % of surface rusted	none
6[C]	extensive rust spots but less than 1 % of surface rusted	No. 6
5	rusting to the extent of 3 % of surface rusted	none
4[D]	rusting to the extent of 10 % of surface rusted	No. 4
3[E]	approximately one sixth of the surface rusted	none
2	approximately one third of the surface rusted	none
1	approximately one half of the surface rusted	none
0[F]	approximately 100 % of surface rusted	unnecessary

[A] Correspond to Swedish Pictorial Standards for Rusting (1955) (black and white).
[B] Corresponds to SSPC Initial Surface Conditions E and British Iron and Steel Research Assn (BISRA) 0.1 %.
[C] Corresponds to SSPC Initial Surface Conditions F and BISRA 1.0 %.
[D] Corresponds to SSPC Initial Surface Condition G.
[E] Rust grades below 4 are of no practical importance in grading performances of paints.
[F] Corresponds to SSPC Initial Surface Condition H.

Standard Test Method for Evaluating Degree of Cracking of Exterior Paints[1]

This standard is issued under the fixed designation D 661; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This test method has been approved for use by agencies of the Department of Defense to replace Method 6471 of Federal Test Method Standard No. 141A. Consult the DoD Index of Specifications and Standards for the specific year of issue which has been adopted by the Department of Defense.

1. Scope

1.1 This test method covers the evaluation of the degree of cracking of exterior paints by comparison with photographic standards.

2. Referenced Documents

2.1 *ASTM Standards:*

D 660 Test Method for Evaluating Degree of Checking of Exterior Paints[2]

2.2 *Other Standards:*

Pictorial Standards of Coating Defects Handbook[3]

3. Terminology

3.1 *Definition:*

3.1.1 *cracking*—that phenomenon manifested in paint films by a break extending through to the surface painted. Where this is difficult to determine, the break should be called a crack only if the underlying surface is visible. The use of a magnification of 10 diameters is recommended in cases where it is difficult to differentiate between cracking and checking (see Test Method D 660).

4. Significance and Use

4.1 Cracking failure of paint films can occur in use. This test method provides a means of evaluating the degree of the failure by comparing the pictorial standards.

5. Types of Cracking

5.1 Three types of cracking are recognized:

5.1.1 *Irregular Pattern Type*—Cracking in which the breaks in the film are in no definite pattern.

5.1.2 *Line Type*—Cracking in which the breaks in the film are generally arranged in parallel lines, usually either horizontally or vertically, over the surface of the film. These breaks often follow the line of brush marks.

5.1.3 *Sigmoid Type*—Cracking in which the breaks in the film form a pattern consisting of curves meeting and intersecting, usually on a relatively large scale.

6. Use of Photographic Reference Standards

6.1 The photographic reference standards that are part of this test method and are provided in the *Pictorial Standards of Coating Defects Handbook* are representative of the degree of cracking of exterior paint films. Figures 1 and 2 are for illustration purposes only and should not be used for evaluation.

6.2 The use of the photographic reference standards[3] illustrated in Fig. 1 requires the following precautions:

6.2.1 The accompanying photographic reference standards show line-type cracking only. Irregular and sigmoid-type cracking may also be interpreted from these photographs.

6.2.2 Care must be taken not to confuse various types of failure that may be present on the same surface. This is particularly true in observing cracking and checking. Cracking may very often be an advanced stage of checking and is very often in evidence along with checking and other failures.

6.2.3 It must be realized that the degree of failure will vary over any given area. Therefore, an average portion of the film should be used for comparison. On larger surfaces it is recommended that ratings be made at several locations and the mean and range reported.

6.2.4 Paint films may collect excessive quantities of dirt, which may mask the type and degree of failure. If necessary, dirt should be removed by careful and gentle brushing with a moderately soft brush.

6.2.5 In examining wood panels for cracking failure, the possibility of wood failure should be recognized. This takes the form of a cracking or splitting of the wood itself with a resultant rupture of the paint film. Also, some panels will develop "resin spewing" which will cause early failure by cracking. These points should be taken into consideration in any evaluations.

6.3 For convenience in recording the data obtained, the records should be kept on forms agreed upon between the purchaser and the seller.

7. Precision and Bias

7.1 No precision or bias statement has been established for this test method.

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[1] This test method is under the jurisdiction of ASTM Committee D-1 on Paint and Related Coatings, Materials, and Applications and is the direct responsibility of Subcommittee D01.25 on Pictorial Standards of Coating Defects.

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[2] *Annual Book of ASTM Standards*, Vol 06.01.

[3] Copies of the pictorial photographic reference standards are contained in the publication *Pictorial Standards of Coatings Defects* and may be obtained from the Federation of Societies for Coatings Technology, 492 Norristown Rd., Blue Bell, PA 19422. The silver halide-gelatin photographs are intended to be the only primary reference standards for this method. The reproductions of them in this test method are for the purpose of illustration only.

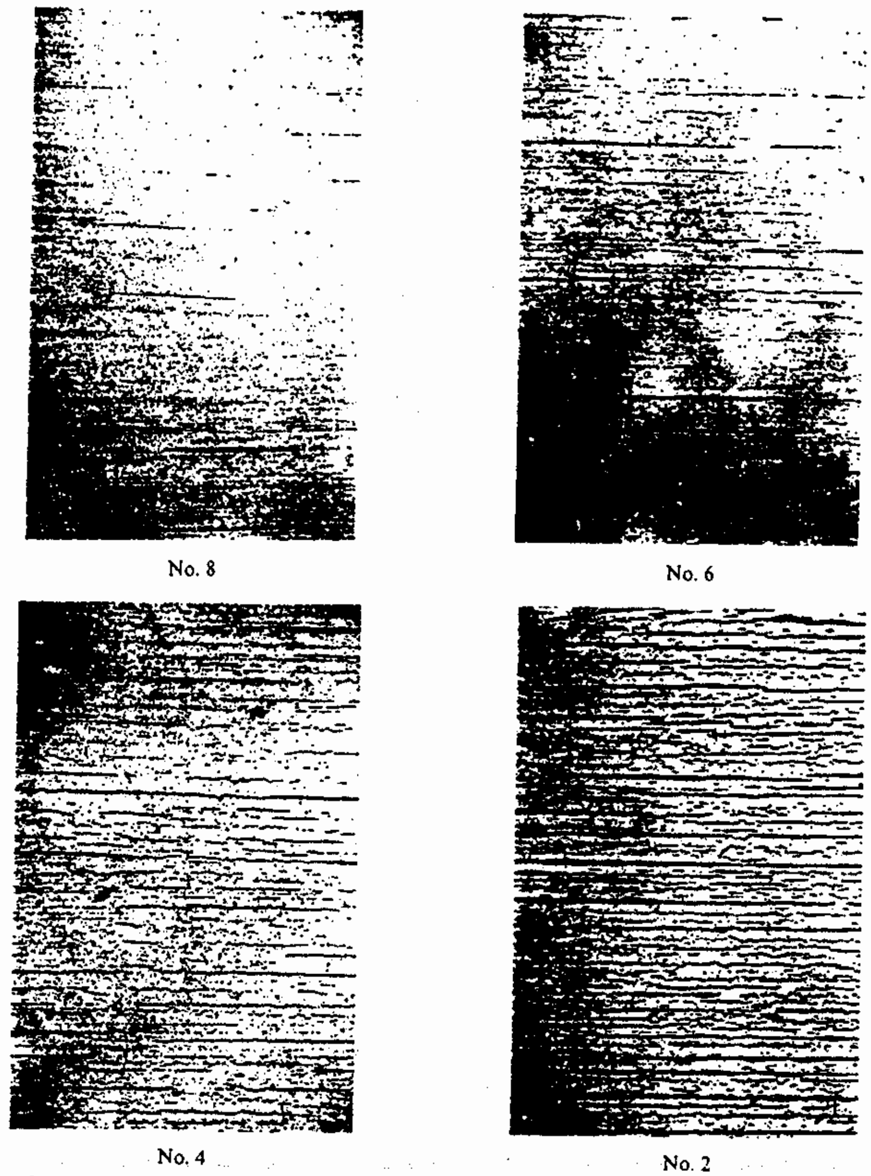

FIG. 1 Degrees of Cracking

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This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, 1916 Race St., Philadelphia, PA 19103.

Designation: D 662 – 93

Standard Test Method for Evaluating Degree of Erosion of Exterior Paints[1]

This standard is issued under the fixed designation D 662; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This test method has been approved for use by agencies of the Department of Defense to replace Method 6431 of Federal Test Method Standard No. 141A. Consult the DoD Index of Specifications and Standards for the specific year of issue which has been adopted by the Department of Defense.

1. Scope

1.1 This test method covers the evaluation of the degree of erosion of exterior paints by comparison with photographic standards.

2. Referenced Documents

2.1 *ASTM Standards:*

D 4214 Method for Evaluating Degree of Chalking of Exterior Paint Film[2]

2.2 *Other Standards:*

Pictorial Standards of Coating Defects Handbook[3]

3. Terminology

3.1 *Definition:*

3.1.1 *erosion*—that phenomenon manifested in paint films by the wearing away of the finish to expose the substrate or undercoat. The degree of failure is dependent on the amount of substrate or undercoat visible. Erosion occurs as the result of chalking. (See Method D 4214 for evaluation of chalking.)

4. Significance and Use

4.1 Erosion failure of paint films can occur in use. This test method provides a mean of evaluating the degree of failure by comparing to pictorial standards.

5. Types of Erosion

5.1 Only one type of erosion is recognized, as defined in Section 3.

6. Use of Photographic Reference Standards

6.1 The photographic reference standards that are part of this test method and are provided in the *Pictorial Standards of Coating Defects Handbook* are representative of the degree of erosion of exterior paint films. Figure 1 is for illustration purposes only and should not be used for evaluation.

6.2 The use of the photographic reference standards[3] illustrated in Fig. 1 requires the following precautions:

6.2.1 Care must be taken not to confuse various types of failure that may be present on the same surface.

6.2.2 It must be realized that the degree of failure will vary over any given area. Therefore, an average portion of the film should be used for comparison. On larger surfaces it is recommended that ratings be made at several locations and the mean and range reported.

6.2.3 The photographic standards used represent various degrees of erosion of a white brushing type paint over a dark primer. This system was necessary to provide sufficient contrast for photographic purposes. The erosion of a film to its normal substrate is, however, readily visible to the naked eye so it may easily be compared to the standards and given a numerical rating.

6.2.4 In doubtful cases, erosion is sometimes more visible in a damp film than in a dry film. Also, with severe erosion, it is often easier to rate the degree of erosion in a damp film than in a dry film.

6.2.5 While erosion of a sprayed film is more regular in its wearing away, a numerical rating can be given to it by interpreting the amount of erosion in terms of these standards.

6.3 For convenience in recording the data obtained, the records should be kept on forms agreed upon between the purchaser and the seller.

7. Precision and Bias

7.1 No precision or bias statement has been established for this test method.

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[1] This test method is under the jurisdiction of ASTM Committee D-1 on Paint and Related Coatings, Materials, and Applications and is the direct responsibility of Subcommittee D01.25 on Pictorial Standards of Coating Defects.

Current edition approved May 15, 1993. Published July 1993. Originally published as D 662 – 42 T. Last previous edition D 662 – 86$^{\epsilon 1}$

[2] *Annual Book of ASTM Standards*, Vol 06.01.

[3] Copies of the pictorial photographic reference standards are contained in the publication *Pictorial Standards of Coatings Defects* and may be obtained from the Federation of Societies for Coatings Technology, 492 Norristown Rd., Blue Bell, PA 19422. The silver halide-gelatin photographs are intended to be the only primary reference standards for this method. The reproductions of them in this test method are for the purpose of illustration only.

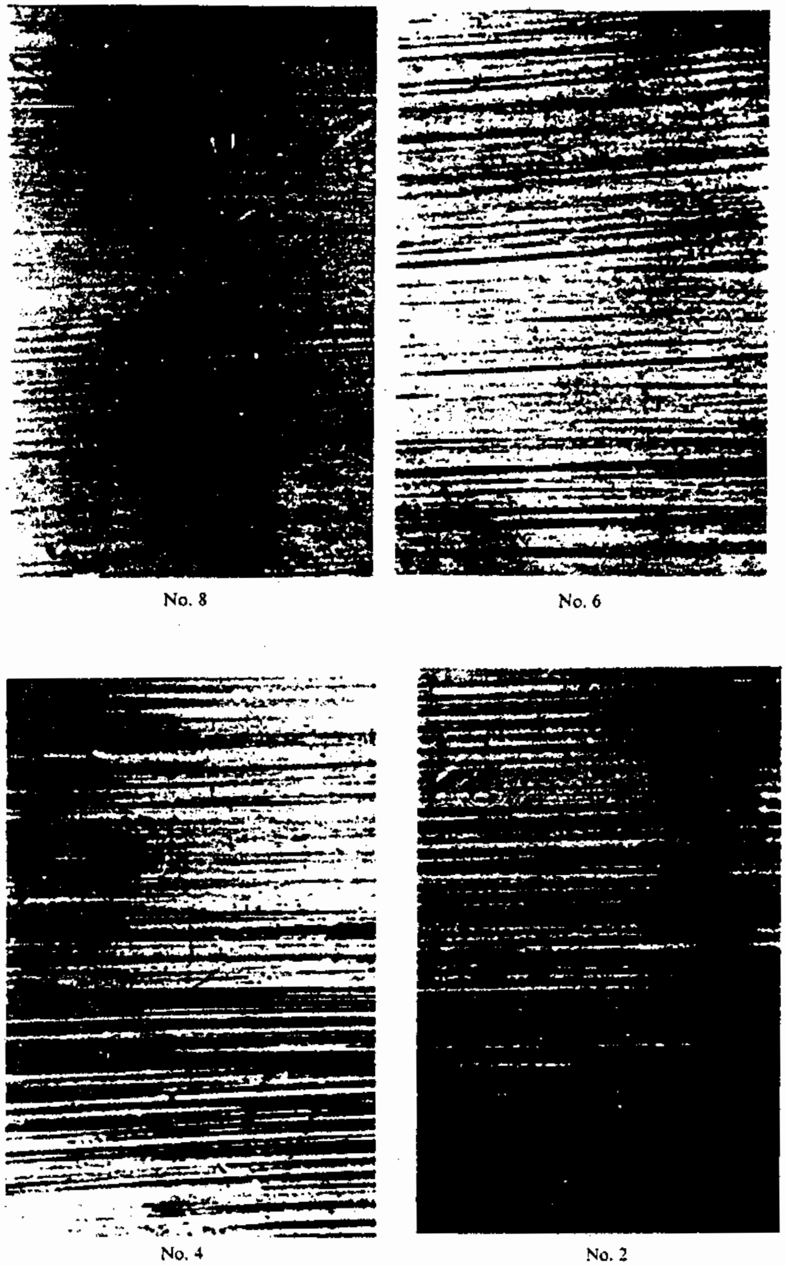

FIG. 1 Degrees of Erosion

Standard Test Method for Evaluating Degree of Blistering of Paints[1]

This standard is issued under the fixed designation D 714; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This test method has been approved for use by agencies of the Department of Defense to replace Method 6461 of Federal Test Method Standard No. 141 A and for listing in the DoD Index of Specifications and Standards.

$^{\epsilon 1}$ NOTE—Keywords were added editorially in October 1994.

1. Scope

1.1 This test method employs photographic reference standards to evaluate the degree of blistering that may develop when paint systems are subjected to conditions which will cause blistering. While primarily intended for use on metal and other nonporous surfaces, this test method may be used to evaluate blisters on porous surfaces, such as wood, if the size of blisters falls within the scope of these reference standards. When the reference standards are used as a specification of performance, the permissible degree of blistering of the paint system shall be agreed upon by the purchaser and the seller.

2. Significance and Use

2.1 A phenomenon peculiar to painted surfaces is the formation of blisters relative to some system weakness. This test method provides a standard procedure of describing the size and density of the blisters so that comparisons of severity can be made.

3. Reference Standards

3.1 The photographic reference standards are glossy prints.[2] Figures 1 to 4 are reproductions of these standards and are included to illustrate two characteristics of blistering: size and frequency.

3.2 *Size*—Reference standards have been selected for four steps as to size on a numerical scale from 10 to 0, in which No. 10 represents no blistering. Blistering standard No. 8 represents the smallest size blister easily seen by the unaided eye. Blistering standards Nos. 6, 4, and 2 represent progressively larger sizes.

3.3 *Frequency*—Reference standards have been selected for four steps in frequency at each step in size, designated as follows:

Dense, *D*,
Medium dense, *MD*,
Medium, *M*, and
Few, *F*.

NOTE 1—A quantitative physical description of blistering would include the following characteristics determined by actual count:
Size distribution in terms of mensuration units,
Frequency of occurrence per unit area,
Pattern of distribution over the surface, and
Shape of blister
For the usual tests, an actual count is more elaborate than is necessary.

4. Procedure

4.1 Subject the paint film to the test conditions agreed upon by the purchaser and the seller. Then evaluate the paint film for the degree of blistering by comparison with the photographic reference standards in Figs. 1 to 4.

5. Report

5.1 Report blistering as a number (Note 2) designating the size of the blisters and a qualitative term or symbol indicating the frequency.

5.2 Intermediate steps in size or frequency of blisters may be judged by interpolation.

5.3 When the distribution of blisters over the area has a nonuniform pattern, use an additional phrase to describe the distribution, such as "small clusters," or "large patches."

NOTE 2—The number refers to the largest size blister that is numerous enough to be representative of the specimen. For example, photographic standard No. 4, "Dense," has blisters ranging in size from about No. 7 to No. 4, inclusive.

6. Keywords

6.1 blistering; corrosion

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[1] This test method is under the jurisdiction of ASTM Committee D-1 on Paint and Related Coatings, Materials, and Applications and is the direct responsibility of Subcommittee D01.25 on Pictorial Standards of Coating Defects.

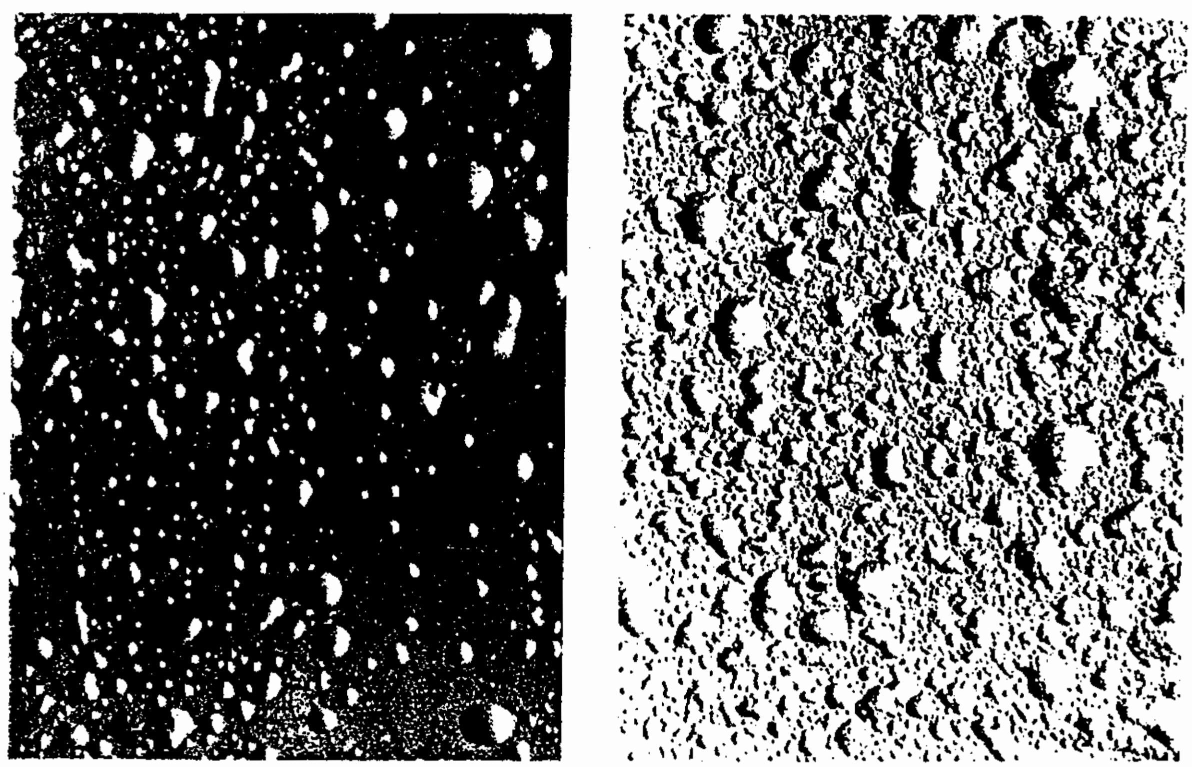
Current edition approved May 29, 1987. Published July 1987. Originally published as D 714 – 43 T. Last previous edition D 714 – 56 (1981).

[2] Glossy prints of the photographic reference standards showing types of blistering are available at a nominal charge from ASTM Headquarters, 1916 Race St., Philadelphia, PA 19103. Request Adjunct No. 12-407140-00.

Few

Medium

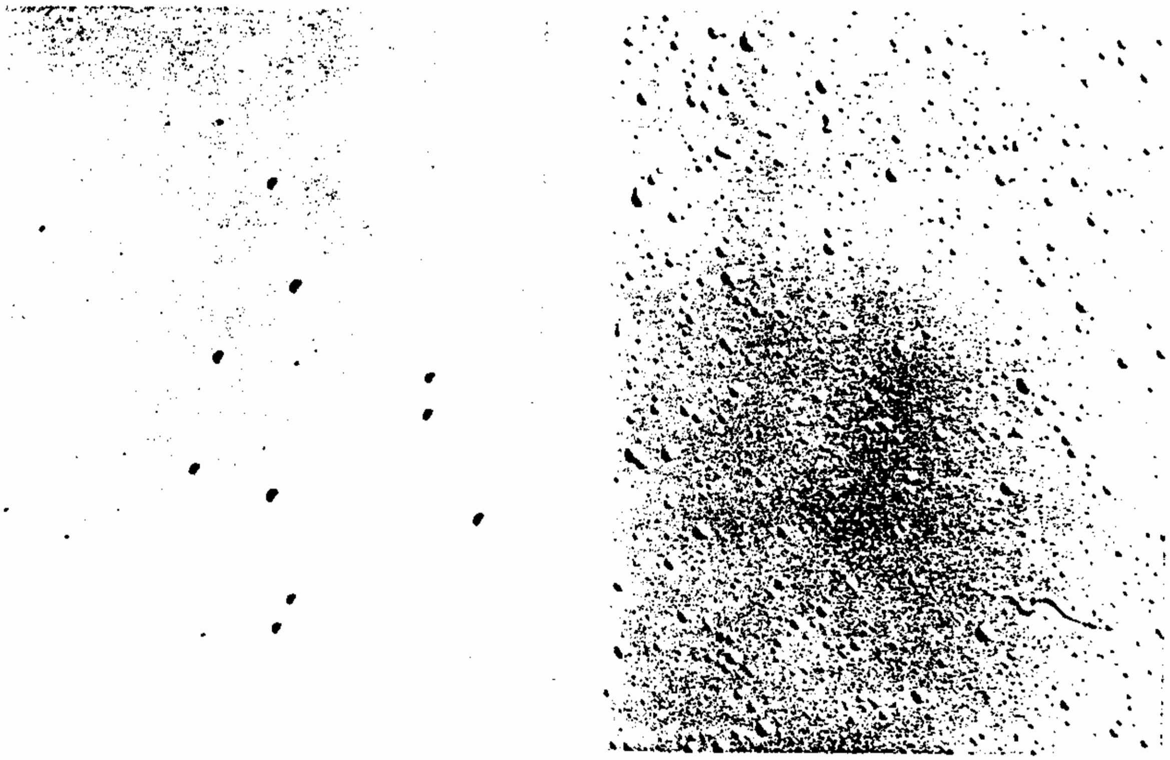
FIG. 1 Blister Size No. 2



Medium Dense

Dense

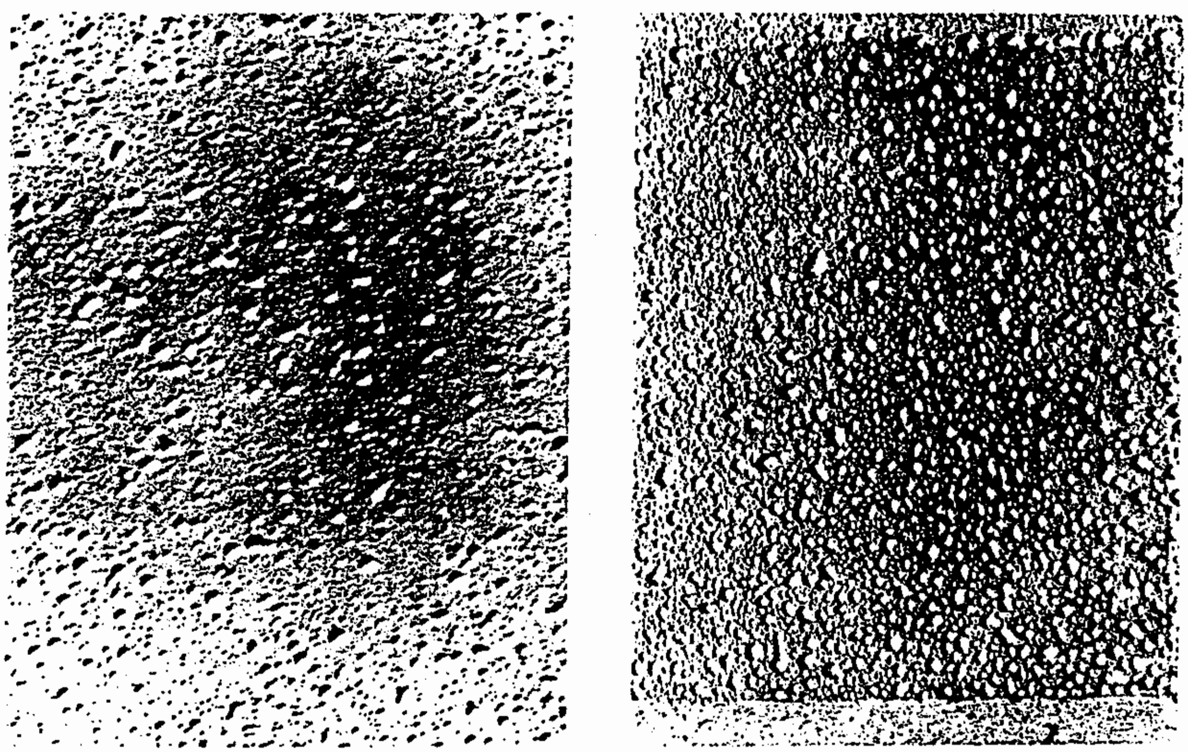
FIG. 1 *Continued*



Few

Medium

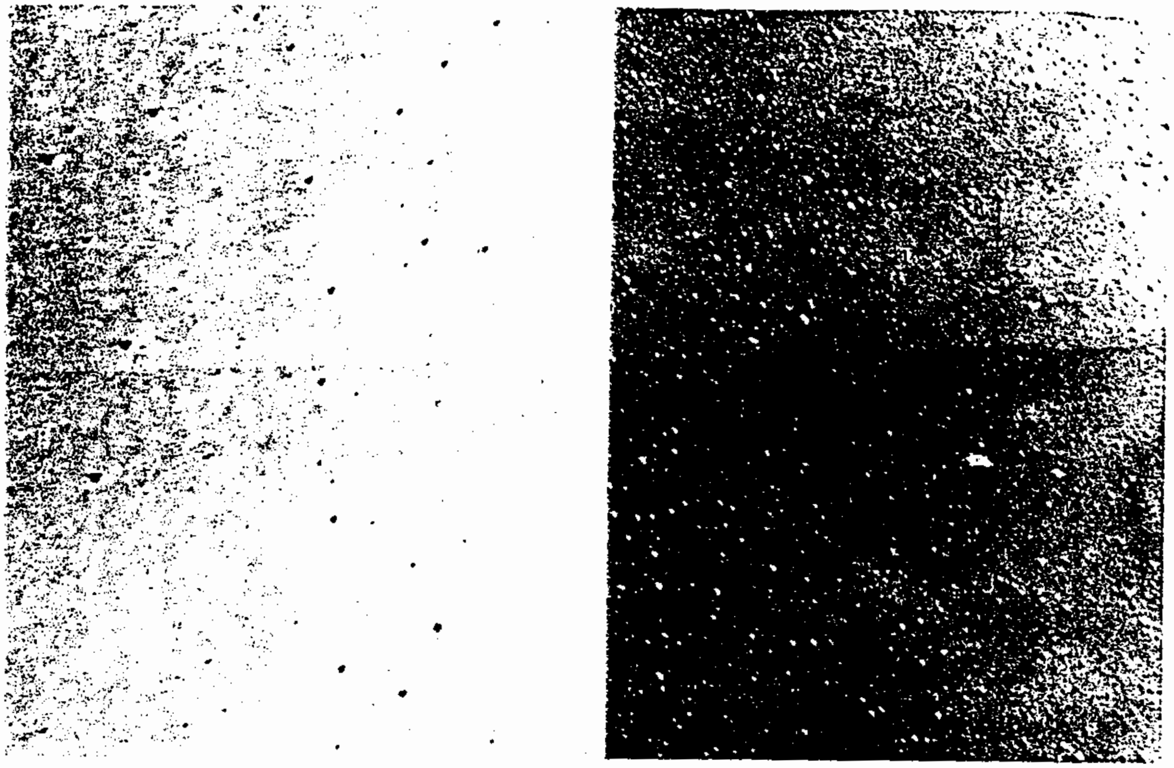
FIG. 2 Blister Size No. 4



Medium Dense

Dense

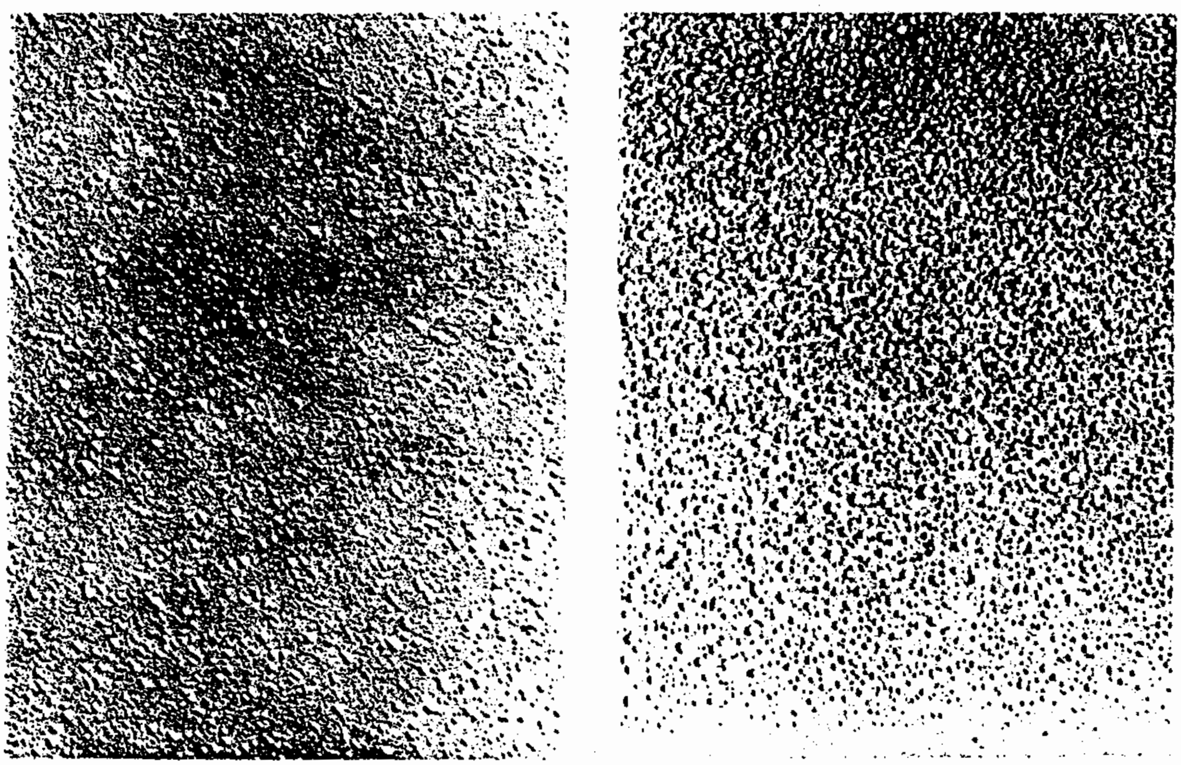
FIG. 2 *Continued*



Few

Medium

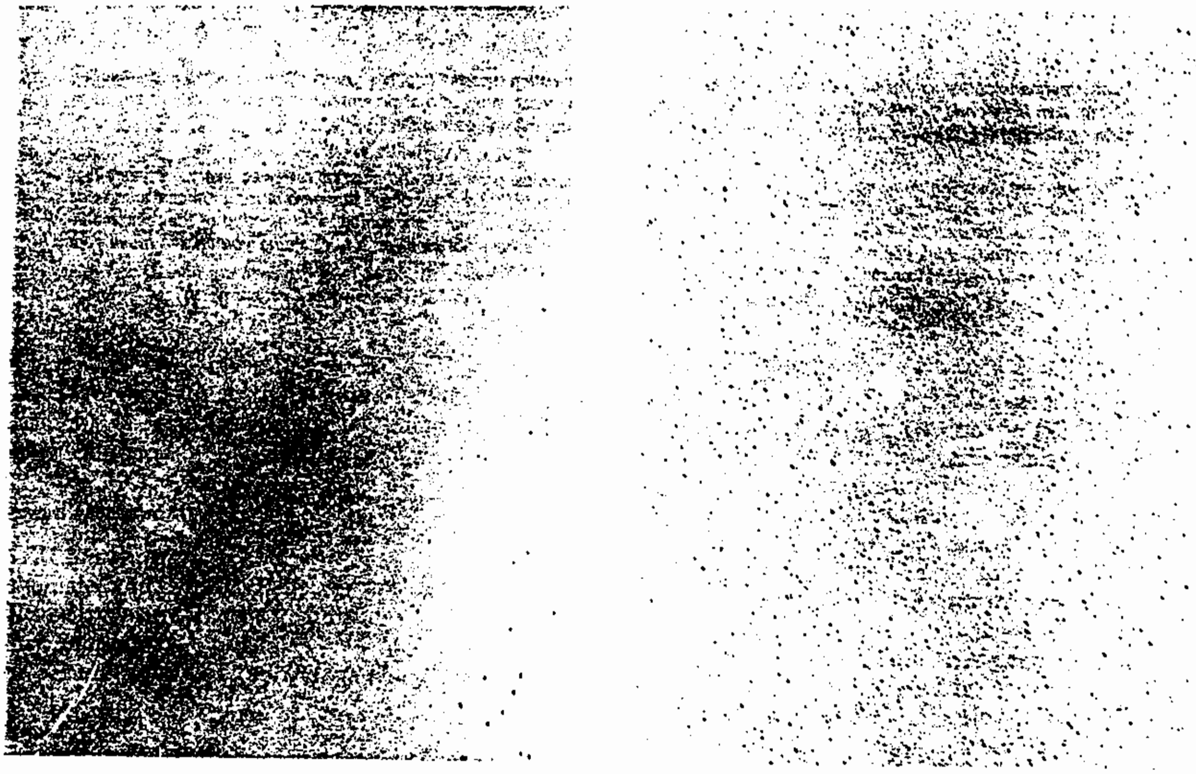
FIG. 3 Blister Size No. 6



Medium Dense

Dense

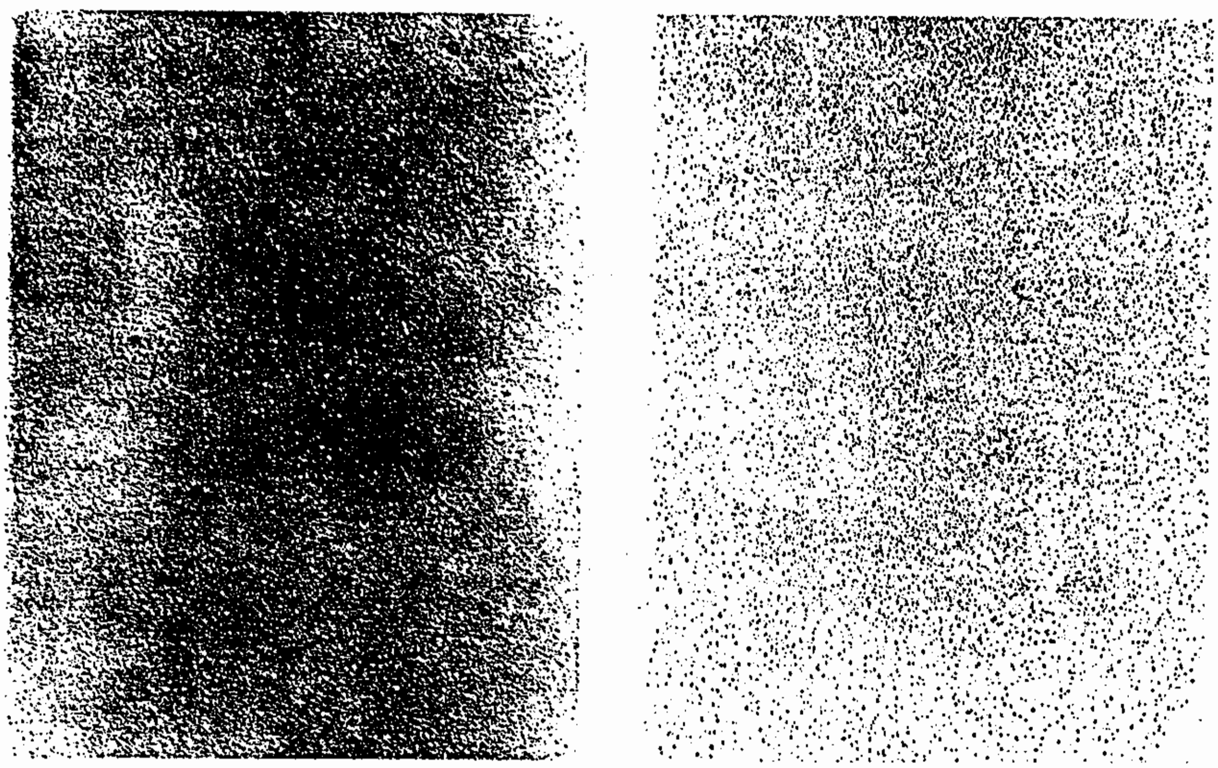
FIG. 3 *Continued*



Few

Medium

FIG. 4 Blister size No. 8



Medium Dense

Dense

FIG. 4 *Continued*

Designation: D 3359 – 95a

Standard Test Methods for Measuring Adhesion by Tape Test[1]

This standard is issued under the fixed designation D 3359; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

These methods have been approved for use by agencies of the Department of Defense. Consult the DoD Index of Specifications and Standards for the specific year of issue which has been adopted by the Department of Defense.

1. Scope

1.1 These test methods cover procedures for assessing the adhesion of coating films to metallic substrates by applying and removing pressure-sensitive tape over cuts made in the film.

1.2 Test Method A is primarily intended for use at job sites while Test Method B is more suitable for use in the laboratory. Also, Test Method B is not considered suitable for films thicker than 5 mils (125 μm).

NOTE 1—Subject to agreement between the purchaser and the seller, Test Method B can be used for thicker films if wider spaced cuts are employed.

1.3 These test methods are used to establish whether the adhesion of a coating to a substrate is at a generally adequate level. They do not distinguish between higher levels of adhesion for which more sophisticated methods of measurement are required.

NOTE 2—It should be recognized that differences in adherability of the coating surface can affect the results obtained with coatings having the same inherent adhesion.

1.4 In multicoat systems adhesion failure may occur between coats so that the adhesion of the coating system to the substrate is not determined.

1.5 The values stated in inch-pound units are to be regarded as the standard. The values given in parentheses are for information only.

1.6 *This standard does not purport to address the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 609 Practice for Preparation of Cold-Rolled Steel Panels for Testing Paint, Varnish, Conversion Coatings, and Related Coating Products[2]

D 823 Practice for Producing Films of Uniform Thickness of Paint, Varnish, and Related Products on Test Panels[2]

D 1000 Test Methods For Pressure-Sensitive Adhesive-Coated Tapes Used for Electrical and Electronic Applications[3]

D 1730 Practices for Preparation of Aluminum and Aluminum-Alloy Surfaces for Painting[4]

D 2092 Practices for Preparation of Zinc-Coated (Galvanized) Steel Surfaces for Painting[5]

D 2197 Test Methods for Adhesion of Organic Coatings by Scrape Adhesion[2]

D 2370 Test Method for Tensile Properties of Organic Coatings[2]

D 3330 Test Method for Peel Adhesion of Pressure-Sensitive Tape of 180° Angle[6]

D 3924 Specification for Standard Environment for Conditioning and Tesing Paint, Varnish, Lacquers, and Related Materials[2]

D 4060 Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser[2]

3. Summary of Test Methods

3.1 *Test Method A*—An X-cut is made in the film to the substrate, pressure-sensitive tape is applied over the cut and then removed, and adhesion is assessed qualitatively on the 0 to 5 scale.

3.2 *Test Method B*—A lattice pattern with either six or eleven cuts in each direction is made in the film to the substrate, pressure-sensitive tape is applied over the lattice and then removed, and adhesion is evaluated by comparison with descriptions and illustrations.

4. Significance and Use

4.1 If a coating is to fulfill its function of protecting or decorating a substrate, it must adhere to it for the expected service life. Because the substrate and its surface preparation (or lack of it) has a drastic effect on the adhesion of coatings, a method of evaluation adhesion of a coating to different substrates or surface treatments, or of different coatings to the same substrate and treatment, is of considerable usefulness in the industry.

4.2 The limitations of all adhesion methods and the specific limitation of this test method to lower levels of adhesion (see 1.3) should be recognized before using it. The intra- and inter-laboratory precision of this test method is similar to other widely-accepted tests for coated substrates

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[1] These test methods are under the jurisdiction of ASTM Committee D-1 on Paint and Related Coatings, Materials, and Applications and are the direct responsibility of Subcommittee D01.23 on Physical Properties of Applied Paint Films.

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[2] *Annual Book of ASTM Standards*, Vol 06.01.

[3] *Annual Book of ASTM Standards*, Vol 10.01.

[4] *Annual Book of ASTM Standards*, Vol 02.05.

[5] *Annual Book of ASTM Standards*, Vol 06.02.

[6] *Annual Book of ASTM Standards*, Vol 15.09.

(for example, Test Method D 2370 and Test Method D 4060), but this is partly the result of it being insensitive to all but large differences in adhesion. The limited scale of 0 to 5 was selected deliberately to avoid a false impression of being sensitive.

TEST METHOD A—X-CUT TAPE TEST

5. Apparatus and Materials

5.1 *Cutting Tool*—Sharp razor blade, scalpel, knife or other cutting devices. It is of particular importance that the cutting edges be in good condition.

5.2 *Cutting Guide*—Steel or other hard metal straightedge to ensure straight cuts.

5.3 *Tape*-One-inch (25-mm) wide semitransparent pressure-sensitive tape with an adhesion strength agreed upon by the supplier and the user is needed[7]. Because of the variability in adhesion strength from batch-to-batch and with time, it is essential that tape from the same batch be used when tests are to be run in different laboratories. If this is not possible the test method should be used only for ranking a series of test coatings.

5.4 *Rubber Eraser*, on the end of a pencil.

5.5 *Illumination*—A light source is helpful in determining whether the cuts have been made through the film to the substrate.

6. Test Specimens

6.1 When this test method is used in the field, the specimen is the coated structure or article on which the adhesion is to be evaluated.

6.2 For laboratory use apply the materials to be tested to panels of the composition and surface conditions on which it is desired to determine the adhesion.

NOTE 3—Applicable test panel description and surface preparation methods are given in Practice D 609 and Practices D 1730 and D 2092.

NOTE 4—Coatings should be applied in accordance with Practice D 823, or as agreed upon between the purchaser and the seller.

NOTE 5—If desired or specified, the coated test panels may be subjected to a preliminary exposure such as water immersion, salt spray, or high humidity before conducting the tape test. The conditions and time of exposure will be governed by ultimate coating use or shall be agreed upon between the purchaser and seller.

7. Procedure

7.1 Select an area free of blemishes and minor surface imperfections. For tests in the field, ensure that the surface is clean and dry. Extremes in temperature or relative humidity may affect the adhesion of the tape or the coating.

7.2 Make two cuts in the film each about 1.5 in. (40 mm) long that intersect near their middle with a smaller angle of between 30 and 45°. When making the incisions, use the straightedge and cut through the coating to the substrate in one steady motion.

7.3 Inspect the incisions for reflection of light from the metal substrate to establish that the coating film has been penetrated. If the substrate has not been reached make another X in a different location. Do not attempt to deepen a previous cut as this may affect adhesion along the incision.

7.4 Remove two complete laps of the pressure-sensitive tape from the roll and discard. Remove an additional length at a steady (that is, not jerked) rate and cut a piece about 3 in. (75 mm) long.

7.5 Place the center of the tape at the intersection of the cuts with the tape running in the same direction as the smaller angles. Smooth the tape into place by finger in the area of the incisions and then rub firmly with the eraser on the end of a pencil. The color under the transparent tape is a useful indication of when good contact has been made.

7.6 Within 90 ± 30 s of application, remove the tape by seizing the free end and pulling it off rapidly (not jerked) back upon itself at as close to an angle of 180° as possible.

7.7 Inspect the X-cut area for removal of coating from the substrate or previous coating and rate the adhesion in accordance with the following scale:

5A No peeling or removal,
4A Trace peeling or removal along incisions or at their intersection,
3A Jagged removal along incisions up to 1/16 in. (1.6 mm) on either side,
2A Jagged removal along most of incisions up to 1/8 in. (3.2 mm) on either side,
1A Removal from most of the area of the X under the tape, and
0A Removal beyond the area of the X.

7.8 Repeat the test in two other locations on each test panel. For large structures make sufficient tests to ensure that the adhesion evaluation is representative of the whole surface.

7.9 After making several cuts examine the cutting edge and, if necessary, remove any flat spots or wire-edge by abrading lightly on a fine oil stone before using again. Discard cutting tools that develop nicks or other defects that tear the film.

8. Report

8.1 Report the number of tests, their mean and range, and for coating systems, where the failure occurred that is, between first coat and substrate, between first and second coat, etc.

8.2 For field tests report the structure or article tested, the location and the environmental conditions at the time of testing.

8.3 For test panels report the substrate employed, the type of coating, the method of cure, and the environmental conditions at the time of testing.

8.4 If the adhesion strength of the tape has been determined in accordance with Test Methods D 1000 or D 3330, report the results with the adhesion rating(s). If the adhesion strength of the tape has not been determined, report the specific tape used and its manufacturer.

9. Precision and Bias[8]

9.1 In an interlaboratory study of this test method in which operators in six laboratories made one adhesion measurement on three panels each of three coatings covering

[7] Permacel 99 manufactured by Permacel, New Brunswick, NJ 08903, and available from various Permacel tape distributors, is reported to be suitable for this purpose. The manufacturer of this tape and the manufacturer of the tape used in the interlaboratory study (see RR: D01-1008), have advised this subcommittee that the properties of these tapes were changed. Users of it should, therefore, check whether current material gives comparable results to previous supplied material.

[8] Supporting data are available from ASTM Headquarters. Request RR: D01-1008.

a wide range of adhesion, the within-laboratories standard deviation was found to be 0.33 and the between-laboratories 0.44. Based on these standard deviations, the following criteria should be used for judging the acceptability of results at the 95 % confidence level:

9.1.1 *Repeatability*—Provided adhesion is uniform over a large surface, results obtained by the same operator should be considered suspect if they differ by more than 1 rating unit for two measurements.

9.1.2 *Reproducibility*—Two results, each the mean of triplicates, obtained by different operators should be considered suspect if they differ by more than 1.5 rating units.

9.2 Bias cannot be established for these test methods.

TEST METHOD B—CROSS-CUT TAPE TEST

10. Apparatus and Materials

10.1 *Cutting Tool*—Sharp razor blade, scalpel, knife or other cutting device having a cutting edge angle between 15 and 30° that will make either a single cut or several cuts at once[9]. It is of particular importance that the cutting edge or edges be in good condition.

10.2 *Cutting Guide*—If cuts are made manually (as opposed to a mechanical apparatus) a steel or other hard metal straightedge or template to ensure straight cuts.

10.3 *Rule*—Tempered steel rule graduated in 0.5 mm for measuring individual cuts.

10.4 *Tape*, as described in 5.3.

10.5 *Rubber Eraser*, on the end of a pencil.

10.6 *Illumination*, as described in 5.5.

10.7 *Magnifying Glass*—An illuminated magnifier to be used while making individual cuts and examining the test area.

11. Test Specimens

11.1 Test specimens shall be as described in Section 6. It should be noted, however, that multitip cutters provide good results only on test areas sufficiently plane[10] that all cutting edges contact the substrate to the same degree. Check for flatness with a straight edge such as that of the tempered steel rule (10.3).

12. Procedure

12.1 Where required or when agreed upon, subject the specimens to a preliminary test before conducting the tape test (see Note 3). After drying or testing the coating, conduct the tape test at room temperature as defined in Specification D 3924, unless D 3924 standard temperature is required or agreed.

12.2 Select an area free of blemishes and minor surface imperfections, place on a firm base, and under the illuminated magnifier, make parallel cuts as follows:

12.2.1 For coatings having a dry film thickness up to and including 2.0 mils (50 μm) space the cuts 1 mm apart and make eleven cuts unless otherwise agreed upon.

12.2.2 For coatings having a dry film thickness between 2.0 mils (50 μm) and 5 mils (125 μm), space the cuts 2 mm apart and make six cuts. For films thicker than 5 mils use Test Method A.[11]

12.2.3 Make all cuts about ¾ in. (20 mm) long. Cut through the film to the substrate in one steady motion using just sufficient pressure on the cutting tool to have the cutting edge reach the substrate. When making successive single cuts with the aid of a guide, place the guide on the uncut area.

12.3 After making the required cuts brush the film lightly with a soft brush or tissue to remove any detached flakes or ribbons of coatings.

12.4 Examine the cutting edge and, if necessary, remove any flat spots or wire-edge by abrading lightly on a fine oil stone. Make the additional number of cuts at 90° to and centered on the original cuts.

12.5 Brush the area as before and inspect the incisions for reflection of light from the substrate. If the metal has not been reached make another grid in a different location.

12.6 Remove two complete laps of tape and discard.

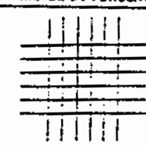
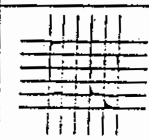
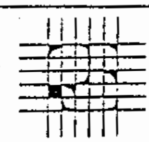
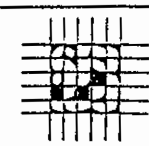
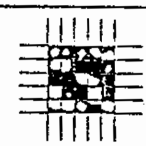
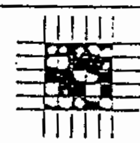
CLASSIFICATION OF ADHESION TEST RESULTS		
CLASSIFICATION	PERCENT AREA REMOVED	SURFACE OF CROSS-CUT AREA FROM WHICH FLAKING HAS OCCURRED FOR SIX PARALLEL CUTS AND ADHESION RANGE BY PERCENT
5B	0% None	
4B	Less than 5%	
3B	5 - 15%	 
2B	15 - 35%	 
1B	35 - 65%	 
0B	Greater than 65%	

FIG. 1 Classification of Adhesion Test Results

[9] Multiblade cutters are available from a few sources that specialize in testing equipment for the paint industry. One supplier that has assisted in the refinement of these methods and of Test Methods D 2197 is given in footnote 10.

[10] A multitip cutter for coated pipe surfaces is now available from Paul N. Gardner Co., 316 NE First St., Pompano Beach, FL 33060.

[11] Test Method B has been used successfully by some people on coatings less than 5 mils by spacing the cuts 5 mm apart. However, the precision values given in 14.1 do not apply as they are based on coatings less than 5 mm in thickness.

Remove an additional length at a steady (that is, not jerked) e and cut a piece about 3 in. (75 mm) long.

12.7 Place the center of the tape over the grid and in the area of the grid smooth into place by a finger. To ensure good contact with the film rub the tape firmly with the eraser on the end of a pencil. The color under the tape is a useful indication of when good contact has been made.

12.8 Within 90 ± 30 s of application, remove the tape by seizing the free end and rapidly (not jerked) back upon itself at as close to an angle of 180° as possible.

12.9 Inspect the grid area for removal of coating from the substrate or from a previous coating using the illuminated magnifier. Rate the adhesion in accordance with the following scale illustrated in Fig. 1:

5B The edges of the cuts are completely smooth; none of the squares of the lattice is detached.
4B Small flakes of the coating are detached at intersections; less than 5 % of the area is affected.
3B Small flakes of the coating are detached along edges and at intersections of cuts. The area affected is 5 to 15 % of the lattice.
2B The coating has flaked along the edges and on parts of the squares. The area affected is 15 to 35 % of the lattice.
1B The coating has flaked along the edges of cuts in large ribbons and whole squares have detached. The area affected is 35 to 65 % of the lattice.
0B Flaking and detachment worse than Grade 1.

12.10 Repeat the test in two other locations on each test panel.

13. Report

13.1 Report the number of tests, their mean and range, ıd for coating systems, where the failure occurred, that is, between first coat and substrate, between first and second coat, etc.

13.2 Report the substrate employed, the type of coating and the method of cure.

13.3 If the adhesion strength has been determined in accordance with Test Methods D 1000 or D 3330, report the results with the adhesion rating(s). If the adhesion strength of the tape has not been determined, report the specific tape used and its manufacturer.

14. Precision and Bias[8]

14.1 On the basis of two interlaboratory tests of this test method in one of which operators in six laboratories made one adhesion measurement on three panels each of three coatings covering a wide range of adhesion and in the other operators in six laboratories made three measurements on two panels each of four different coatings applied over two other coatings, the pooled standard deviations for within- and between-laboratories were found to be 0.37 and 0.7. Based on these standard deviations, the following criteria should be used for judging the acceptability of results at the 95 % confidence level:

14.1.1 *Repeatability*—Provided adhesion is uniform over a large surface, results obtained by the same operator should be considered suspect if they differ by more than one rating unit for two measurements.

14.1.2 *Reproducibility*—Two results, each the mean of duplicates or triplicates, obtained by different operators should be considered suspect if they differ by more than two rating units.

14.2 Bias cannot be established for these test methods.

15. Keywords

15.1 adhesion, tape; crosscut adhesion test method; tape adhesion test method; X-cut adhesion test method

APPENDIX

(Nonmandatory Information)

X1. COMMENTARY

X1.1 Introduction

X1.1.1 Given the complexities of the adhesion process, can adhesion be measured? As Mittal (**1**)[12] has pointed out, the answer is both yes and no. It is reasonable to state that at the present time no test exists that can precisely assess the actual physical strength of an adhesive bond. But it can also be said that it is possible to obtain an indication of relative adhesion performance.

X1.1.2 Practical adhesion test methods are generally of two types: "*implied*" and "*direct*". "Implied" tests include indentation or scribe techniques, rub testing, and wear testing. Criticism of these tests arises when they are used to quantify the strength of adhesive bonding. But this, in fact, is not their purpose. An "implied" test should be used to assess coating performance under actual service conditions. "Direct" measurements, on the other hand, are intended expressly to measure adhesion. Meaningful tests of this type are highly sought after, primarily because the results are expressed by a single discrete quantity, the force required to rupture the coating/substrate bond under prescribed conditions. Direct tests include the Hesiometer and the Adherometer (**2**). Common methods which approach the direct tests are peel, lap-shear, and tensile tests.

X1.2 Test Methods

X1.2.1 In practice, numerous types of tests have been used to attempt to evaluate adhesion by inducing bond rupture by different modes. Criteria deemed essential for a test to warrant large-scale acceptance are: use of a straightforward and unambiguous procedure; relevance to its intended application; repeatability and reproducibility; and quantifiability, including a meaningful rating scale for assessing performance.

X1.2.2 Test methods used for coatings on metals are: peel adhesion or "tape testing"; Gardner impact flexibility testing; and adhesive joint testing including shear (lap joint) and

[12] The boldface numbers in parentheses refer to the list of references at the end of this test method.

direct tensile (butt joint) testing. These tests do not strictly meet all the criteria listed, but an appealing aspect of these tests is that in most cases the equipment/instrumentation is readily available or can be obtained at reasonable cost.

X1.2.3 A wide diversity of tests methods have been developed over the years that measure aspects of adhesion **(1–5)**. There generally is difficulty, however, in relating these tests to basic adhesion phenomena.

X1.3 The Tape Test

X1.3.1 By far the most prevalent test for evaluating coating "adhesion" is the tape-and-peel test, which has been used since the 1930's. In its simplest version a piece of adhesive tape is pressed against the paint film and the resistance to and degree of film removal observed when the tape is pulled off. Since an intact film with appreciable adhesion is frequently not removed at all, the severity of the test is usually enhanced by cutting into the film a figure *X* or a cross hatched pattern, before applying and removing the tape. Adhesion is then rated by comparing film removed against an established rating scale. If an intact film is peeled cleanly by the tape, or if it debonds just by cutting into it without applying tape, then the adhesion is rated simply as poor or very poor, a more precise evaluation of such films not being within the capability of this test.

X1.3.2 The current widely-used version was first published in 1974; two test methods are covered in this standard. Both test methods are used to establish whether the adhesion of a coating to a substrate is at an adequate level; however they do not distinguish between higher levels of adhesion for which more sophisticated methods of measurement are required. Major limitations of the tape test are its low sensitivity, applicabiity only to coatings of relatively low bond strengths, and non-determination of adhesion to the substrate where failure occurs within a single coat, as when testing primers alone, or within or between coats in multicoat systems. For multicoat systems where adhesion failure may occur between or within coats, the adhesion of the coating system to the substrate is not determined.

X1.3.3 Repeatability within one rating unit is generally observed for coatings on metals for both methods, with reproducibility of one to two units. The tape test enjoys widespread popularity and is viewed as "simple" as well as low in cost. Applied to metals, it is economical to perform, lends itself to job site application, and most importantly, after decades of use, people feel comfortable with it.

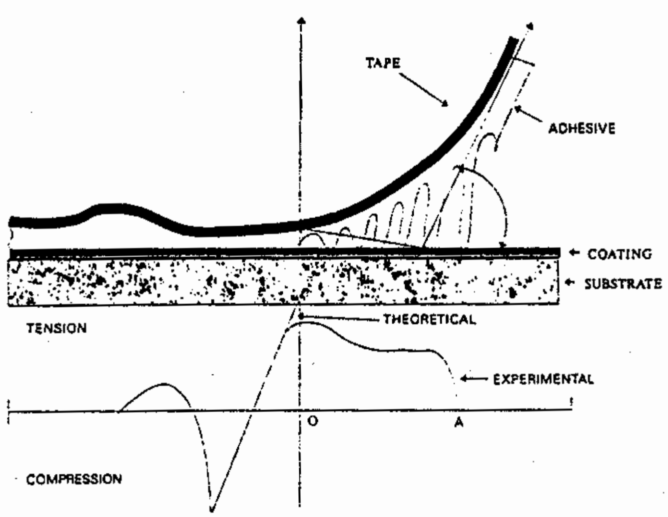


FIG. X1.1 Peel Profile (6)

X1.3.4 When a flexible adhesive tape is applied to a coated rigid substrate surface and then removed, the removal process has been described in terms of the "peel phenomenon," as illustrated in Fig. X1.1.

X1.3.5 Peeling begins at the "toothed" leading edge (at the right) and proceeds along the coating adhesive/interface or the coating/substrate interface, depending on the relative bond strengths. It is assumed that coating removal occurs when the tensile force generated along the latter interface, which is a function of the rheological properties of the backing and adhesive layer materials, is greater than the bond strength at the coating-substrate interface (or cohesive strength of the coating). In actuality, however, this force is distributed over a discrete distance (O-A) in Fig. X1.1, which relates directly to the properties described, not concentrated at a point (O) in Fig. X1.1 as in the theoretical case—though the tensile force is greatest at the origin for both. A significant compressive force arises from the response of the tape backing material to being stretched. Thus both tensile and compressive forces are involved in adhesion tape testing.

X1.3.6 Close scrutiny of the tape test with respect to the nature of the tape employed and certain aspects of the procedure itself reveal several factors, each or any combination of which can dramatically affect the results of the test as discussed **(6)**.

X1.4 Peel Adhesion Testing on Plastic Substrates

X1.4.1 Tape tests have been criticized when used for substrates other than metal, such as plastics. The central issues are that the test on plastics lacks reproducibility and does not relate to the intended application. Both concerns are well founded: poor precision is a direct result of several factors intrinsic to the materials employed and the procedure itself. More importantly, in this instance the test is being applied beyond its intended scope. These test methods were designed for relatively ductile coatings applied to metal substrates, not for coatings (often brittle) applied to plastic parts **(7)**. The unique functional requirements of coatings on plastic substrates cause the usual tape tests to be unsatisfactory for measuring adhesion performance in practice.

X1.5 The Tape Controversy

X1.5.1 With the withdrawal from commerce of the tape specified originally, 3M No. 710, current test methods no longer identify a specific tape. Differences in tapes used can lead to different results as small changes in backing stiffness and adhesive rheology cause large changes in the tension area. Some commercial tapes are manufactured to meet minimum standards. A given lot may surpass these standards and thus be suitable for general market distribution; however, such a lot may be a source of serious and unexpected error in assessing adhesion. One commercially available tape test kit had included a tape with adhesion strength variations of up to 50 % claimed by the manufacturer. Also, because tapes change on storage, bond strengths of the tape may change over time **(7, 8)**.

X1.5.2 While there are tapes available that appear to deliver consistent performance, a given tape does not adhere equally well to all coatings. For example, when the peel removal force of the tape (from the coating) used earlier by Task Group D01.23.10 to establish precision of the method, by 3M No. 710 was examined with seven different electromagnetic interference/radio frequency interference (EMI/RFI) coatings, it was found that, while peel was indeed consistent for a given coating, the value varied by 25 % between the highest and lowest ratings among coatings. Several factors that contribute to these differences include coating composition and topology: as a result, no single tape is likely to be suitable for testing all coatings. Further, the tape test does not give an absolute value for the force required for bond rupture, but serves only as an indicator that some minimum value for bond strength was met or exceeded (**7, 8**).

X1.6 Procedural Problems

X1.6.1 The tape test is operator intensive. By design it was made as simple as possible to perform, and requires a minimum of specialized equipment and materials that must meet certain specifications. The accuracy and precision depend largely upon the skill of the operator and the operator's ability to perform the test in a consistent manner. Key steps that directly reflect the importance of operator skill include the angle and rate of tape removal and the visual assessment of the tested sample. It is not unexpected that different operators might obtain different results (**7, 8**).

X1.6.2 *Peel Angle and Rate:* The standard requires that the free end of the tape be removed rapidly at as close to a 180° angle as possible. If the peel angle and rate vary, the force required to remove the tape can change dramatically. Nearly linear increases were observed in peel force approaching 100 % as peel angle was changed from 135 to 180, and similar large differences can be expected in peel force as peel rate varies. These effects are related as they reflect certain rheological properties of the backing and adhesive that are molecular in origin. Variation in pull rate and peel angle can effect large differences in test values and must be minimized to assure reproducibility (**9**).

X1.6.3 *Visual Assessment:* The final step in the test is visual assessment of the coating removed from the specimen. which is subjective in nature, so that the coatings can vary among individuals evaluating the same specimen (**9**).

X1.6.3.1 Performance in the tape test is based on the amount of coating removed compared to a descriptive scale. The exposure of the substrate can be due to factors other than coating adhesion, including that arising from the requirement that the coating be cut (hence the synonym "cross-hatch adhesion test"). Justification for the cutting step is reasonable as cutting provides a free edge from which peeling can begin without having to overcome the cohesive strength of the coating layer.

X1.6.3.2 Cutting might be suitable for coatings applied to metal substrates, but for coatings applied to plastics or wood. the process can lead to a misleading indication of poor adhesion due to the unique interfacial zone. For coatings on soft substrates, issues include how deep should this cut penetrate, and is it possible to cut only to the interface?

X1.6.3.3 In general, if adhesion test panels are examined microscopically, it is often clearly evident that the coating removal results from substrate failure at or below the interface, and not from the adhesive failure between the coating and the substrate. Cohesive failure within the coating film is also frequently observed. However, with the tape test, failures within the substrate or coating layers are rare because the tape adhesive is not usually strong enough to exceed the cohesive strengths of normal substrates and organic coatings. Although some rather brittle coatings may exhibit cohesive failure, the tape test adhesion method does not make provision for giving failure locality (**7, 8**).

X1.6.4 Use of the test method in the field can lead to variation in test results due to temperature and humidity changes and their effect upon tape, coating and substrate.

X1.7 Conclusion

X1.7.1 All the issues aside, if these test methods are used within the Scope Section and are performed carefully, some insight into the approximate, relative level of adhesion can be gained.

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